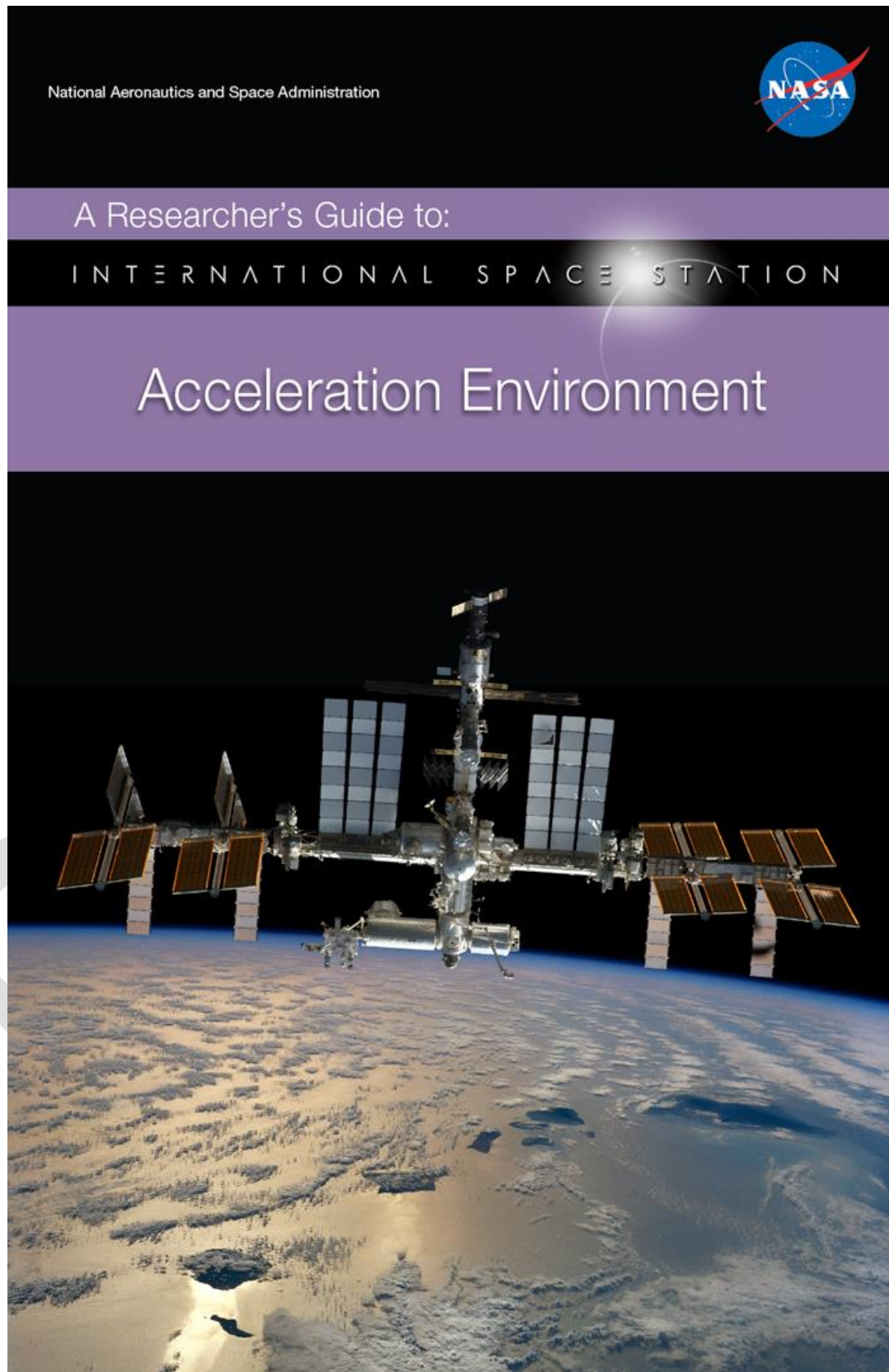


# ACCELERATION ENVIRONMENT

\*\*\* DRAFT \*\*\*



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## 1 Components of Microgravity Environment

The microgravity environment of any orbiting spacecraft such as the International Space Station (ISS) is not truly "zero G" as sometimes assumed. This popular idiom applies only to the vehicle's center of mass, an infinitesimal point that is not necessarily part of the spacecraft's structure. In theory, the center of mass can reside outside of the space station. All the rest of the mass that comprise the vehicle or are otherwise attached to it will experience accelerations from a variety of sources, such as pumps, fans, attitude control thrusters, atmospheric drag, rotational forces and others. These accelerations are often referred to as disturbances in that they can introduce undesired effects. These disturbances are mostly transmitted mechanically through the vehicle structure or acoustically through the air within the habitable modules.

A prismatic view of the ISS acceleration environment reveals a broad spectrum of vibrational frequencies, ranging from the relatively low-magnitude, low-frequency portion referred to as the quasi-steady regime up through the relatively high-frequency, high-magnitude vibratory regime. Typically, the magnitude of these vibrations varies with frequency, ranging on the order of less than  $1 \times 10^{-5}$  m/s<sup>2</sup> at very low-frequencies to over  $1 \times 10^{-1}$  m/s<sup>2</sup> at higher frequencies. To put this in other terms, the ISS acceleration spectrum ranges from on the order of less than a micro-g at the low-frequency end to over ten milli-g at the high-frequency end of the spectrum. Another aspect of the acceleration environment to consider is the transient regime, which is associated with relatively brief and relatively high-magnitude accelerations, such as those introduced by a vehicle docking, thruster firing, or even a crew push-off or landing. These impulsive events do not fall neatly into either the quasi-steady regime or the vibratory regime. When we consider its spectral decomposition, we see that this type of disturbance has impact over a wide portion of the acceleration spectrum.

Why use the label microgravity? Well, if we consider only the low-frequency, low-magnitude accelerations, then we note that those are approximately one-millionth of what would be experienced at the surface of the Earth – one-millionth, hence the prefix "micro". This label, of course, is oversimplified and not intended to completely characterize the dynamic acceleration environment of the ISS. See Figure 1 Microgravity Environment Components for an overview of microgravity environment acceleration components.

### 1.1 The Quasi-Steady Regime

The quasi-steady regime is comprised of accelerations at the lower end of the spectrum (below 0.01 hertz) and with magnitudes on the order of less than a micro-g. At very low frequencies, the space station can be approximated by a rigid-body, which implies a global nature for these accelerations. These low-frequency disturbances are associated with phenomena related to the ISS orbital rate of about 90 minutes, and due primarily to aerodynamic drag and vehicle rotation. The drag exerted on the space station comes from a thin atmosphere that exists even at a nominal altitude of about 200 miles. This drag varies as the ISS traverses a slightly elliptical orbit through the atmosphere with thermal variations throughout. Denser portions give rise to more drag and thus higher acceleration levels. In its nominal attitude (+XVV +ZLV), the aerodynamic drag exerted on the ISS is primarily manifested on the two axes aligned with its orbital trajectory. One axis is aligned with the local vertical axis (the Z-axis), and one axis is aligned with the velocity vector or direction of travel (the X-axis). See Figure 2 Space Station Analysis (SSA) Coordinate System for a depiction of this attitude and a description of the Space Station Analysis (SSA) coordinate system.

Gravity gradient and rotational effects are key factors in shaping the quasi-steady regime. Both of these factors depend on the location of interest relative to the vehicle's center of mass. The gravity gradient component stems from the fact that Earth's gravitational tug decreases according to the inverse-square law, whereby the lower part of the orbiting structure will get a slightly stronger tug from the Earth. Rotational effects come about from the attitude maintained by the ISS. In essence, the space station tumbles or rotates once per orbit.

Two other sources of acceleration to consider in the quasi-steady regime are the occasional, relatively brief attitude maneuver and reboost events. Attitude maneuvers might be for debris avoidance, but these are rare. More often, these attitude maneuvers are used to align the space station for docking by another vehicle. The altitude of the space station slowly decreases as it spirals inward toward the Earth over time. As a result, an occasional propulsive reboost is needed to raise the altitude. This is typically accomplished by the use of thrusters on the Progress cargo vehicle. These thrusters are fired or pulsed for several minutes and act primarily in the direction of travel (the X-axis) to increase the velocity in that direction and thereby spiraling the station's trajectory outward again until the desired altitude is reached.

### 1.2 The Vibratory Regime

The vibratory regime is comprised of vibrations in the acceleration spectrum above 0.01 hertz. These vibrations result from motion of the vehicle, crew, or experiment-related equipment. The omnipresent flexing and bending of vehicle structure, crew sleep/wake cycles, crew exercise, turbulent airflow, and rotating/reciprocating machinery are some of the

disturbance sources that play a role in shaping this vibratory regime. In general, as the vibrational frequency under consideration increases, the more localized the effect of these disturbances tends to be. Vehicle subsystems such as those needed for life support, thermal control, or communications produce significant disturbances here. The impact of these is primarily a function of proximity to the disturbance source. In a similar way, experiment-related equipment needed to support or conduct scientific investigations on the space station can play a major role, particularly as disturbances to other payloads in their vicinity.

### 1.2.1 Vehicle Structural Modes

Vehicle structural modes reside at the low-frequency end of the vibratory portion of the acceleration spectrum. These vibrations fall within the frequency range from about 0.1 hertz to about 5 hertz. These vibrations arise from the excitation of natural frequencies associated with large components of the space station structure, such as the main truss, and with fundamental appendage modes, such as solar arrays. These structures are excited by relatively large magnitude, relatively brief impulsive events like during a reboost. The driving excitation of a reboost results in large, albeit short-lived, response amplitudes as structural ringing damps out. Also, relatively small magnitude vibrations at just the right frequency will give rise to structural resonance. Structural vibrations propagate via mechanical linkage and transmission. While the frequency of these disturbances may be registered the same throughout the space station, their amplitude is a function of location. Structural mode vibrations tend to be low amplitude during crew sleep periods relative to crew active periods owing to the absence of impulsive push-off and landing events by the crew on space station structure.

For assembly complete, the first such structural mode of the ISS, sometimes referred to as “mode one”, is nominally at about 0.1 hertz. This frequency can change slightly due to thermal or other effects. While small, this change in frequency can have significant, deleterious effects when control/structure interaction takes place. An undesired dynamic coupling can arise between attitude control actuation and the space station structure. The vehicle loads and dynamics team at the Johnson Space Center (JSC) keeps track of mode one via daily updates of PIMS web products at the Glenn Research Center (GRC) and alerts flight controllers in Houston or Moscow when the situation dictates. During quiet periods such as crew sleep, the spectral amplitude of the narrowband peak at mode one is about an order of magnitude less than otherwise for measurement locations in the USL. The color spectrogram in Figure 3 Spectrogram Showing Mode One with Crew Sudden Transition to Wake shows mode one as the faint, yellow horizontal trace at about 0.1 hertz that becomes noticeable when the crew wakes with a sudden transition just after Greenwich Mean Time (GMT) 06:00. Conversely, the color spectrogram in Figure 4 Spectrogram Showing Mode One with Crew Slow Transition to Sleep for that same day shows mode one along with other structural vibrations tapering off after GMT 21:00 with transition toward weaker (blue) magnitudes.

In the JEM and in the COL, mode one is about two orders of magnitude less during quiet periods. In addition to mode one, there is a cluster of modes below 5 hertz that further characterize the vibrations of large space station structures. These are noted along with the location of the Space Acceleration Measurement System (SAMS) sensors that captured this persistent set of vibrations in Table 1 Partial List of Vehicle Structural Modes\*.

**Table 1 Partial List of Vehicle Structural Modes\***

f (hertz)*	SENSOR LOCATION			
	ALL	LAB	COL	JEM
0.10	x			
0.18	x			
0.25			x	
0.28		x		x
0.41		x		x
0.60		x		x
0.71		x		x
0.83		x		
0.87			x	x
1.13		x		
1.28		x		
1.30			x	x
1.62		x		
1.65			x	x
1.84		x		x
1.95		x		
1.98		x		x
2.25		x		
2.30				x
2.50				x

\* note that closely spaced modes can appear as a single peak in a power spectral density (PSD) for a given frequency resolution and that was not accounted for in this analysis; therefore, closely spaced modes may be represented as a single value in the table above.

When we consider the concentration of structural modes between about  $0.06 < f < 3$  hertz in aggregate, we note that SAMS sensors mounted in the USL register RMS acceleration levels between about 20 and 30 ug in this band, while SAMS sensors mounted in the JEM and the COL register RMS levels closer to 40 ug.

### 1.2.2 Crew Exercise

Next in the vibratory regime, we examine crew exercise. Exercise is an important part of the crew's daily routine. In addition to promoting fitness, this activity is geared to help prevent bone and muscle loss associated with prolonged exposure to microgravity. On average, each crew member is scheduled to exercise approximately two hours per day and with multiple crew members, many of their scheduled periods overlap on the daily timeline. There are three basic types of exercise equipment that the crew can use including a treadmill, a cycle ergometer and a resistive apparatus.

The space station has one treadmill in Node 3 referred to as "T2" and another one in the Service Module, which is called the Treadmill with Vibration Isolation and Stabilization (TVIS). The TVIS is suspended over an opening in the floor, which allows for movement of the treadmill into and back out of this opening. The vibration isolation system serves to minimize the transfer of exercise forces from the treadmill to space station structure. There are a couple of cycle ergometers on the ISS: the Cycle Ergometer with Vibration Isolation System (CEVIS) located in the USL, and the Veloergometer (Velo) located in the Service Module. These devices provide controlled workloads for the crew. The CEVIS is located in the USL where the astronauts strap themselves in. The CEVIS was designed to counteract crew motions in order to attenuate the transfer of its vibratory disturbances to the space station. The last type of exercise equipment comes in the form of the Advanced Resistive Exercise Device (ARED) located in Node 3. This is a resistive device that simulates gravity. The ARED provides the capability to do both upper and lower-body exercises including squats, dead lifts, heel raises, bicep curls, and bench press. This equipment has built-in vibration isolation as well.

In general, these exercise equipment were designed for use onboard the space station and with quiescent microgravity environment maintenance in mind. However, factors outside of their design envelope can play a role in this activity having an impact on the environment. As a result, this activity can excite vehicle structural modes depending on the frequency of exercise movement and on the vigor of the crew. In addition, exercise can introduce its own, unique signature in the vibratory regime. Typically, these signatures are manifest below about 3 hertz. The color spectrogram of Figure 5 Spectrogram Showing Crew Exercise Periods and Relative Quiet Period shows a couple of bouts of exercise between about GMT 10:00 and 11:00 with the strongest impact (red horizontal streaks) seen below 3 hertz. Interesting to note in this figure also is the relative quiet crew period ending at about GMT 13:30 as indicated by the vertical dark blue region.

### 1.2.3 Urine Processor Assembly (UPA)

Another noticeable, but weak, disturbance source in the vibratory regime is the UPA, which is part of the ISS water recovery system in Node 3. The UPA houses a distillation assembly centrifuge that was designed to spin at 220 rpm (3.67 hertz). Onboard acceleration measurements indicate that it often rotates closer to 221 rpm (3.68 hertz). This equipment routinely operates continuously for several hours at a time and leaves a faint, yet distinct narrowband signature in the acceleration spectrum. The impact of this disturbance was measured by SAMS in the USL, and is also evident in SAMS measurements from the COL. The signature from this equipment, however, is much less clear in the JEM. To summarize, the UPA injects a weak narrowband signature at just over 3.6 hertz. This narrowband disturbance is most distinctive in the USL, with RMS levels of around 38 ug at the SAMS es06 sensor location; with RMS levels in the JEM of about 6 ug at the SAMS 121f05 sensor location. For more information on this disturbance source see [http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb\\_vib\\_vehicle\\_upa\\_rev\\_2011\\_12\\_22.pdf](http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb_vib_vehicle_upa_rev_2011_12_22.pdf). Also, use Table 2 in the next subsection as a reference for sensor locations on the ISS.

### 1.2.4 Ku-Band Antenna

The Ku-band antenna provides a link for payload communications between the ISS and ground stations throughout the world. The antenna is also referred to as the space-to-ground antenna (SGANT) and is mounted on a two-axis gimbal assembly to allow the dish to rotate for acquisition and line-of-sight tracking of data relay satellites. The vibratory signature of the Ku-band antenna is persistent and distributed mainly over the frequency range from about 5 hertz to about 20 hertz. Extended durations of auto-tracking while locked on current target satellite are punctuated by occasional, brief spatial acquisition iterations to lock on to the next target satellite and the vibratory motions associated with these functions are seen as twin spectral peaks at about 5.2 hertz and 7.8 hertz. Superimposed, there is a broad spectral hump between about 5 and 8 hertz, which gets registered to varying degrees throughout the ISS. The magnitude of this disturbance at any given sensor location is not a function of quiet versus nominal periods, like sleep versus wake, because this communications link is maintained around the clock; it does vary with time though. For the most part, its impact as a disturbance source is dependent on measurement location. The table below shows representative values:

**Table 2 Ku-Band Antenna, RMS Values (5 < f < 20 hertz)**

Sensor	RMS (ug)	LAB	Location
SAMS 121f08	210	COL	COL1A1, ER3, Seat Track near D1
MMA 0bbd	204	JEM	JPM A3 Upper Left
SAMS 121f05	108	JEM	JPM1F5, ER4, Drawer 2
SAMS 121f04	99	USL	LAB1O2, ER1, Lower Z Panel
SAMS 121f03	72	USL	LAB1O1, ER2, Lower Z Panel
SAMS 121f02	136	USL	LAB1S2, MSG, Upper Left Seat Track
SAMS TSH es06	109	USL	LAB1S4, FIR

For the narrowband nature of the brief acquisition handover periods, see the spectral peaks at 5.2 hertz, and 7.8 hertz in Figure 6 Spectrogram Showing Ku-Band Acquisition Signature; not seen in this figure are two more narrowband spectral peaks at 10.6 hertz and 13.1 hertz.

In summary, the Ku-band antenna described in this section is the dominant disturbance source from about 5 hertz to about 20 hertz at all acceleration sensor locations analyzed by the PIMS team. Its acceleration signature is characterized by a semi-regular pattern of frequency sweeps that are evident on a time scale of an orbital period. Measurements show this disturbance source registers loudest at the SAMS 121f08 location in the COL at about 210 ugRMS.

### 1.2.5 Russian SKV Air Conditioner

The Russian SKV air conditioner is part of the Environmental Control and Life Support System (ECLSS). This equipment gives rise to another common vibratory disturbance that shows up at all sensor measurement locations. It is tightly controlled in frequency producing narrowband vibrations at 23.5 hertz. These vibrations were measured as loudest in the USL at the 121f03 and 121f04 locations at about 29 ugRMS.

### 1.2.6 SAMS Fan

There is a SAMS fan that produces a narrowband vibration at 47 hertz. This disturbance is only detectable at sensor locations near ER1 in the USL. At the SAMS 121f04 location, it is registered with an RMS level of about 174 ug.



## **1.2.7 General Laboratory Active Cryogenic International Space Station Experiment Refrigerator (GLACIER)**

The GLACIER is a water-cooled freezer that provides cryogenic transportation and preservation of samples requiring temperatures as low as minus 160 degrees Celsius. Acceleration spectral analysis shows the vibratory impact of this equipment was focused primarily in three narrowband peaks at 60 hertz, 120 hertz, and 180 hertz. Since these are common operating frequencies, it is likely that some of the energy in these bands is attributable to other equipment as well. Acceleration measurements indicate the epicenter of this disturbance's 60 hertz component is in the USL near ER1 (the 121f04 location at about 1027 ugRMS), and it was also loud near ER2 (the 121f03 location at about 911 ugRMS) and to a much lesser extent near the MSG (the 121f02 location at about 97 ugRMS). The other components shake out as follows: the 120 hertz component was loudest at 121f03 location at about 369 ugRMS, next at 121f04 location at about 227 ugRMS, and least so at 121f02 location at about 102 ugRMS. The 180 hertz component had the lowest impact with 194 ugRMS at 121f04 location, 133 ugRMS at 121f03 location, and 41 ugRMS at 121f02 location, and it was not distinguishable at the JAXA MMA 0bbd sensor location.

## **1.2.8 Common Cabin Air Assembly (CCAA)**

The Common Cabin Air Assembly (CCAA) in the USL provides the capability to control the cabin air temperature, maintain the humidity level within desired limits and generate ventilation air flow. During a normal shutdown operation of the CCAA, the inlet fan speed is reduced from about 5700 RPM (about 95 hertz) to about 3400 RPM (about 57 hertz). At that point, the water separator continues to operate at about 5900 RPM (about 98 hertz) for approximately three hours to accomplish dry-out prior to final shutdown. Both fans are then shut down during the transition from the port side CCAA to the starboard CCAA. Operation of the water separator results in the primary impact of this system on the microgravity environment. The water separator has a narrowband signature at about 98 hertz and imparts RMS levels as follows: about 557 ugRMS at the 121f03 location, 397 ugRMS at the 121f02 location, 232 ugRMS at the 121f04 location, and 39 ugRMS at the SAMS es06 location.

## **1.2.9 Control Moment Gyroscopes (CMGs)**

There are four control moment gyroscopes (CMGs) located on the Z1 truss structure of the ISS. These rotate at 6600 revolutions per minute (RPM) to provide angular momentum. The immutable laws of physics allow flight controllers to tap into inherent torque and use it as a non-propulsive means of attitude control for the space station. As seen by the narrow spectral peak at 110 hertz in the figure at this link [http://pims.grc.nasa.gov/plots/batch/year2013/month01/day03/2013\\_01\\_03\\_00\\_00\\_00.000\\_121f03\\_pcscs\\_roadmaps500.pdf](http://pims.grc.nasa.gov/plots/batch/year2013/month01/day03/2013_01_03_00_00_00.000_121f03_pcscs_roadmaps500.pdf), these gyros are tightly controlled in frequency and register most distinctly in the USL with RMS levels of about 61, 65, and 111 ugRMS at the 121f02, 121f04, and 121f03 sensor locations, respectively.

## **1.3 The Transient Regime**

The transient regime describes accelerations that are impulsive in nature. That is, brief yet relatively large amplitude accelerations that can often excite structural modes. These accelerations are associated with events like thruster firings for reboosts or attitude maneuvers, which are more globally felt and can include crew push-offs and landings, which tend to be more localized. An example of this type of disturbance is documented at this link [http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb\\_vib\\_vehicle\\_progress50p\\_docking.pdf](http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb_vib_vehicle_progress50p_docking.pdf).

## **2 Acceleration Environment Feedback Model**

The microgravity acceleration environment of the ISS is quite dynamic. The user community is diverse with concerns ranging from structural integrity of the vehicle to experiment resonances and sensitivities. See Figure 7 Acceleration Environment Feedback Model for an overview of the Principal Investigator Microgravity Services (PIMS) team interaction with the user community. The PIMS project supports Microgravity Research Program Office (MRPO) Principal Investigators in the science disciplines of biotechnology, combustion science, fluid physics, materials science and fundamental physics. PIMS plays an active role throughout the experiment life cycle with involvement and support during experiment planning, performance and evaluation of results.

### **2.1 Pre-Experiment Services**

PIMS contributes to experiment teams through acceleration data analysis specific to their particular science. This effort is augmented by more general efforts aimed at educating microgravity Principal Investigators about reduced-gravity



experiment platforms' environments and about the accelerometer systems available to measure the environments of those platforms. This involvement with experiment teams during experiment planning stages results in the collection of acceleration data best suited for correlation with measured science data. A fundamental role of the PIMS project's acceleration data support efforts is to archive and disseminate acceleration data. The archival of acceleration data provides investigators the means to determine the environment under which their experiments were conducted and potentially help to plan their future work. PIMS utilizes the archived data to support users interested in the microgravity acceleration environment by providing information about activities and acceleration sources. The result of this accumulated knowledge base is an improved understanding of the expected environment of the various reduced gravity platforms that is passed on to investigator teams during the experiment planning process.

## **2.2 Experiment Operations**

In addition to providing the proper microgravity environment education during experiment planning, PIMS works with investigators to design acceleration data displays and analysis techniques best suited for understanding potential relationships between measured acceleration data and the science results. A number of plot options, displays and analysis techniques are currently available to Principal Investigators. Distribution of the acceleration environment information is accomplished primarily through the World Wide Web. The availability of the microgravity acceleration data in near real-time can also be employed by investigators as a tool for making decisions regarding when to initiate experiment operations and how to make adjustments from experiment run to experiment run in order to improve science results. This interaction during experiment operations can help lead to experimental success.

## **2.3 Post-Experiment Feedback**

Post-experiment analysis and interpretation of acceleration data can be the missing puzzle piece for investigators trying to determine what factors either helped or hindered their results. Correlation with the acceleration record can help expand their existing knowledge base and, in turn, serve those who follow in their footsteps or toward future, follow-on investigations.

## **3 Acceleration System Description**

The NASA Glenn Research Center (GRC) is home to many key components of the ISS acceleration measurement and analysis program. The GRC has the long-established goal to provide timely and readily accessible acceleration data and related information. Foremost in this pursuit is to capture, process, and archive the acceleration measurements, which continuously stream from the space station. Furthermore, it offers analysis services for the microgravity community in general and with the capability to provide tailored products for scientific payloads, structural dynamics monitoring, and technology developers. As a means to fulfill its acceleration program goals, the GRC sponsors the Space Acceleration Measurement System (SAMS), the Microgravity Acceleration Measurement System (MAMS), and the Principal Investigator Microgravity Services (PIMS) projects.

### **3.1 Space Acceleration Measurement System (SAMS)**

SAMS has been a cornerstone in the ongoing effort to provide continuous access to the vibratory environment on the ISS. This system has a proven track record of sustained, reliable performance. It first flew in June 1991 and has flown on nearly every major microgravity science mission on the Space Shuttle. In addition, SAMS was used for four years aboard the Russian space station, Mir, where it measured accelerations in support of scientific investigations. SAMS has been onboard the ISS since 2001. It has streamed acceleration measurement data nearly continuously since then in support of principal investigators, technology developers, and the microgravity community at-large. Last, but certainly not least, SAMS also plays an integral role in daily loads and dynamics monitoring and feeds into the detailed analysis aimed at preserving structural integrity and possibly extending the longevity of the ISS as a microgravity research platform.

SAMS has ability to instrument and measure the local vibratory regime ( $0.01 < f < 300$  hertz) in all three of the ISS laboratories, including throughout the USL. The accelerations it measures arise from vehicle activities and subsystems, experiment operations, crew movements, and structural dynamics. SAMS Remote Triaxial Sensor (RTS) systems are used primarily to monitor the local vibratory environment for individual experiments requiring acceleration measurement support, and for daily vehicle structural monitoring. Each RTS is capable of measuring acceleration disturbances between 0.01 hertz and 400 hertz. Each RTS consists of two components: the RTS sensor enclosure (SE), and the RTS electronics enclosure (EE). The RTS-SE, is mounted as close to the experiment as possible. There, it measures and translates the data into a digital signal, which gets routed to its RTS-EE. The RTS-EE, in turn, sends the acceleration data to the SAMS Interim Control Unit (ICU). The RTS-EE also provides power and command signals for up to two attached RTS-SEs. See Figure 8 On-Orbit Photo of SAMS Sensor in USL during Expedition 4 for an on-orbit photograph of a SAMS sensor head in the USL during Expedition 4.

An additional sensor called the RTS Ethernet Standalone (RTS-ES) is available for acceleration measurement support. The RTS-ES is capable of making acceleration measurements in standalone fashion, and therefore does not require an RTS-EE for power or for command/data routing.

All SAMS RTSs are linked together by the ICU, which coordinates the command and telemetry data for the various RTS systems being used throughout the ISS. All acceleration data obtained by each SAMS RTS are routed to the ICU for downlink to the ground. The command and control for each RTS is accomplished through the ICU, which has a laptop computer with a Linux operating system as its main component. Once the ICU receives the measurements from the RTS systems, it checks the data for completeness, breaks the data into well-defined information packets, and then sends those packets to the SAMS Ground Operations Equipment located at the Telescience Support Center (TSC) at the GRC.

The SAMS ICU is scheduled to be upgraded in 2013. This upgrade will leverage improvements to both the hardware and software that it relies on for its core functionality. Once this upgrade is in place, the SAMS control unit hardware will be interchangeable with any of the space station laptop computers currently in the onboard pool of spares. The new hardware gives SAMS the ability to support the entire foreseeable life cycle of the ISS, while the new software gives the ground operations team improvements in commanding capability and streaming log files for improved monitoring.

### **3.2 Microgravity Acceleration Measurement System (MAMS)**

MAMS has also played a long-standing role in providing continuous access to the acceleration environment on the ISS. However, in this case, the MAMS primarily monitors the quasi-steady acceleration regime ( $f < 0.01$  hertz) of the space station. It consists of two accelerometer subsystems: the OARE Sensor Subsystem (OSS), and the High-Resolution Accelerometer Package (HiRAP). The OSS is its low-frequency sensor, which was uniquely designed to characterize the quasi-steady environment of the space station for both scientific payloads and vehicle teams. The HiRAP is a vibratory sensor that monitors the local vibratory environment up to 100 hertz at the MAMS location on the ISS. MAMS is located in LAB1O2 (ER1) of the USL. The OSS data are typically trimmed-mean filtered to better extract the quasi-steady acceleration information (below 0.01 hertz) from its raw measurements. This low-magnitude, low-frequency data is thus rendered and ready to be mapped to any arbitrary location on the space station using rigid-body assumptions.

The MAMS measurements serve to complement the SAMS for comprehensive coverage of the ISS acceleration environment. The MAMS provides global, quasi-steady information below 0.01 hertz, while the SAMS gives the localized vibratory acceleration environment between 0.01 and 300 hertz. In this way, analysts, investigators, and researchers have access to the entire spectrum of disturbances that may affect what interests them.

### **3.3 Principal Investigator Microgravity Services (PIMS)**

The prime directive of the PIMS team is to support principal investigators who are conducting microgravity research on the ISS. PIMS also plays a support role for loads and dynamics analysis with regards to vehicle sustaining engineering. In general, PIMS ongoing efforts aim to qualify, quantify, and otherwise assess and characterize the space station microgravity environment as it evolves in order to capture and convey the acceleration effects on experiments, payloads, and structural dynamics. PIMS also responds to ad hoc user requests that typically include time-based or frequency-based concerns. These requests often give rise to specific, tailored displays and analyses of acceleration measurements and related data. The resulting displays and analyses are either newly developed or refined from existing ones, and bring to front-and-center the specific concerns of researchers or structural dynamics analysts. PIMS then deploys the appropriate suite of resources, displays, and analysis tools to extract features of the acceleration environment that target the investigator's concerns.

For example, the lowest-frequency structural mode, "mode one" of the ISS described earlier has been monitored daily since GMT 09-March-2012 using a tailored product set. These products seek to both qualify and quantify some key vibrational features of the space station's main truss. See Figure 9 Sample of Daily Products Used to Monitor Loads Events for Structural Integrity for an eight-hour example of these plots. This shows qualitatively a zoom-in on the low-end of the structural mode regime with a very fine frequency resolution spectrogram. It also plots features extracted from the vibratory data in the form of RMS acceleration versus time as the topmost subplot in that figure and the frequency of interest (foi) versus time shown in the subplot just above the spectrogram. Based on products like these, it is clear from the analysis of SAMS measurements how this lowest station structural mode has slowly changed over time. Its frequency has fluctuated somewhat around 0.1 hertz and has shown correlation with other station-related phenomena, such as the solar beta angle, vehicle dockings, and so on. While this "mode one" example highlights PIMS contributions to structural monitoring, it should be noted that this work serves primarily as a starting point that leads to more in-depth analysis by vehicle loads and dynamics engineers. It serves as a daily guide as to when the behavior of station structures are status quo or perhaps deserve a more in-depth look. Over the years, engineers have incorporated the wealth of vibratory

measurements from the SAMS into their mathematical models to further identify what factors will govern this mode, when and under what conditions. Ultimately, the empirical information from SAMS has led to improvements of model estimates whereby the ISS program benefits with increased confidence regarding the impact of vehicle load events and, in turn, in engineering estimates of structural life.

The Japanese Aerospace Exploration Agency (JAXA) sponsors and operates the Microgravity Measurement Apparatus (MMA) onboard the ISS. The MMA is dedicated to monitoring and characterizing the local vibratory environment in the Japanese Experiment Module (JEM). The MMA does not operate continuously. It operates as needed to support science via a ground-commanded on/off scenario. After collecting a few days of data, the MMA team at JAXA uploads raw acceleration data files to an FTP server at the NASA GRC. The PIMS team processes these data for inclusion in the acceleration archive hosted by a web server at the NASA GRC.

In addition to roadmap spectrograms and the other web-based products that they produce on a daily basis, the PIMS team also creates and compiles microgravity handbook pages at <http://pims.grc.nasa.gov/handbook>. This handbook is an effort to educate potential users of the ISS as a microgravity platform. It highlights features of the microgravity environment that may be relevant to a particular experiment in some respect. These handbook pages also help to see where opportunities or pitfalls may exist. For example, if a potential user's payload or experiment has a resonant frequency near 24 hertz, then the handbook page that describes the Russian air conditioner may be of interest. The information contained in these handbook pages is not comprehensive, but serve more so from the perspective of a conversation starter. It gives future investigators an idea about what disturbances to expect and is intended to spark follow-up questions about how to use the ISS in their discipline and maybe to motivate follow-up, focused analyses.

#### **4 Acceleration Data Archives**

The Acceleration Measurement Program (AMP) at the NASA GRC receives, archives, processes, analyzes, displays, and shares acceleration measurements from the ISS. The acceleration archive includes data from the SAMS and MAMS, both of which are sponsored by NASA. The archive also includes data from the MMA, which is sponsored and operated within the JEM onboard the ISS by JAXA. Like any good archive, the goal here is to preserve detailed records of the ISS acceleration environment for past, present, and future users of the platform. Those interested in using the acceleration measurement data, can browse starting at this link <http://pims.grc.nasa.gov/ftp/pad>. Alternatively, you can look at some processed data starting at this link <http://pims.grc.nasa.gov/roadmap>. This roadmap view is recommended as a good starting point for those interested in an overview of the ISS microgravity environment as it evolves over time.

The SAMS and MAMS stream data from the ISS nearly continuously and MMA captures data occasionally as needed. In the 12 years between May 3, 2001 and May 3, 2013, the archive at NASA GRC has grown to over 10 terabytes of ISS acceleration measurements from SAMS, MAMS and JAXA's MMA. The longevity of these acceleration measurement systems pays tribute to their robust design plus sustaining engineering and maintenance operations allocated by NASA in the interest of its customers. In the roughly 105,000 hours that have transpired between May 3, 2001 and May 3, 2013, the SAMS and MAMS have accrued over 376,000 hours of acceleration measurements from multiple sensors operating simultaneously. See Figure 10 Acceleration Data Archives for an acceleration archive summary and depiction.

#### **5 Acceleration Environment Handbook**

The PIMS web site makes available to the public a microgravity environment handbook at <http://pims.grc.nasa.gov/handbook>. This handbook is a compilation of information aimed at characterizing specific aspects or features of disturbance sources measured on the ISS. The main categories in this handbook are the acceleration regime for the given entry: quasi-steady, vibratory, or transient. These are further sub-categorized with respect to the disturbance source: crew-, vehicle- or equipment-related. Most handbook entries characterize the disturbance source of interest in two primary ways: qualify and quantify.

First for a handbook entry, there is typically one page dedicated to qualifying the effects of the disturbance source being presented. For the vibratory regime, this is usually a color spectrogram that shows boundaries and structure in both time and frequency. The third dimension on these spectrogram plots is represented by color, which gives a crude indication of magnitude. For the quasi-steady and transient regimes, this qualification is usually in the form of a three-panel, per-axis plot of acceleration versus time.

Secondly for an entry, there is usually a page dedicated to quantifying the effects of the disturbance source. This is intended to address questions like how much or which direction. For the vibratory regime, this quantification is usually some form of RMS plot versus time for a given frequency band. For the quasi-steady and transient regimes, some form of table or plot that depicts average or peak acceleration during the event of interest is the means of quantifying.

Finally, most handbook entries include unique details gleaned from analysis of the acceleration measurements and some handbook entries include interesting or ancillary information that are pertinent or related to the topic at hand. We give three examples in the next three subsections from among the many available on the web: (1) a quasi-steady regime example on reboosts, (2) a vibratory regime example on the Ku-band antenna and (3) a transient regime example on crew push-off.

### **5.1 Quasi-Steady Regime Example, Progress Reboost**

The handbook page titled “Progress Reboost” is quite comprehensive. It provides analysis results from measurements made by MAMS that cover more than 60 reboost events spanning over a decade of ISS history. The first page describes the primary quasi-steady effect of a reboost performed by a Russian Progress cargo vehicle. Recall that aerodynamic drag on the ISS leads to a gradual, inward spiral toward the Earth. Thus, a reboost is needed and achieved by firing thrusters in a direction opposite the direction of flight. As Newtonian mechanics go, the net result is a velocity increase in the direction of travel for the station. A reaction force spirals its trajectory outward to a higher altitude. Examination of this handbook entry shows that the salient features of a reboost are a step up in X-axis acceleration during the several minutes of the event. See this link

[http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb\\_qs\\_vehicle\\_ProgressReboost.pdf](http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb_qs_vehicle_ProgressReboost.pdf).

### **5.2 Vibratory Regime Example, Ku-Band Antenna**

The handbook page titled “Ku-Band Antenna” shows an interesting evolution from an unknown disturbance source. While the vibratory regime can be accurately quantified by the SAMS at up to 1,000 times per second, much of that has not been fully qualified. We do not always know what specific source gives way to the accelerations we measure at the accelerometer locations. The Ku-band antenna is one example of an interesting, nearly continuous vibratory disturber that eventually was identified as a vibratory disturbance source. For investigators with sensitivity or concern between about 5 hertz and 20 hertz, the Ku-band antenna is a vibratory disturbance source that must be considered. Its handbook entry is a good place to start. See this link [http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb\\_vib\\_vehicle\\_ku.pdf](http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb_vib_vehicle_ku.pdf).

### **5.3 Transient Regime Example, Crew Glovebox Push-Off**

The handbook page titled “Crew Glovebox Push-Off” shows the effects of crew push-off events. These come from the interaction between the crew and space station structure that yield relatively brief but large transient accelerations. Typically, these push-off transients are associated with crew locomotion and are accompanied to varying degrees by crew landing on other structure located some distance away. Transient events such as these tend to have two main effects on the microgravity environment: (1) an initial, brief acceleratory spike, followed by (2) ringing excitation of space station structural modes. See this link

[http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb\\_vib\\_crew\\_msgpushoff\\_rev\\_2003\\_09\\_02.pdf](http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb_vib_crew_msgpushoff_rev_2003_09_02.pdf).

## **6 Acceleration Measurement Availability**

The microgravity environment affects your science. Otherwise, you would not be going through the extraordinary measures that are needed to conduct your science on the space station; from ground-based development or pilot studies, station manifest, documentation, review cycles, verification, crew training, launch, deployment and so on through to experiment runs and, in some cases, sample return. Therefore, it is important to consider the effects that the microgravity environment will have on the phenomena you are studying. In some cases, it is important to consider the ancillary apparatus or mechanisms used to observe or gather your results and not just the underlying scientific facets of your investigation.

For example, the vibratory environment at your site might not have deleterious effects on the physical phenomena you are investigating, but the cantilever-mounted thermistor you need to gather temperatures might have a resonant frequency near a persistent disturbance source (e.g., a neighboring pump, fan, etc.) on the station. In any case, knowledge is power, so it behooves your design to develop your experiment and related equipment with knowledge of the microgravity environment to which you experiment will be exposed. In addition, during your actual science runs and data collection, knowledge of the microgravity environment during your critical time frames is important, in some cases paramount, and can lead to improved understanding of your results or the factors that led to those results, good or bad, either way. One such lesson learned came from a liquid-bridge experiment that happened to have a resonant frequency close to a space station structural mode. Investigators used this information for mitigation. They scheduled their critical runs during crew sleep when that structural mode tends to die down. From a microgravity environment user perspective, it is important to consider the spatial, temporal, and spectral aspects of the environment.

In spatial terms, the location and orientation of your experiment can be key factors. For example, proximity to the space station's center of mass dictates much of the quasi-steady acceleration variations your payload will experience. Generally, the closer you are to the center of mass, the more quiescent the quasi-steady acceleration environment. In addition, proximity to other equipment (e.g., an adjacent rack fan, pump, etc.) can play a major role in shaping the vibratory accelerations to which your payload is subjected.

In temporal terms, the daily cycles of crew sleep or occasional vehicle-related events might be a consideration for you. The crew typically wakes daily at GMT 06:00 (although that can vary), and this wake transition can clearly be felt in SAMS vibratory measurements. Also, the space station has a large cross-sectional area, so atmospheric drag causes its orbit to decay over time. As a result, reboosts are scheduled to reclaim its desired altitude. See the following YouTube video for some clear and visible effects of a reboost <http://www.youtube.com/watch?v=8MR3daaWLXI>. Other scheduled events to consider are vehicle dockings and extravehicular activities. A wild card in terms of scheduling is debris avoidance maneuvers. These are unplanned, but vital to safety.

In spectral terms, vehicle structural modes below about 5 hertz, Ku-band antenna motion between about 5 to 17 hertz, rotating or reciprocating equipment for vehicle systems or experiment operations ranging up to 400 hertz, are just some of the constituents of the wide spectrum of vibratory disturbance sources that comprise the vibratory regime.

The solution for acceleration measurement and support for you in all three laboratories of the ISS is the Acceleration Measurement Program (AMP), which is sponsored and managed at the NASA GRC. The AMP offers two independent systems that were designed to give continuous coverage of the ISS acceleration environment from the low-frequency, low-magnitude quasi-steady regime up to the relatively high-frequency, higher-magnitude vibratory regime. The Space Acceleration Measurement System (SAMS) is a distributed system to measure the vibratory environment, while the Microgravity Acceleration Measurement System (MAMS) measures the quasi-steady environment on board the ISS. Both the SAMS and the MAMS have been operating nearly continuously since 2001. The acceleration measurements from these systems are a resource available to assist ISS users with correlating experimental results with the acceleration environment. In addition, the Principal Investigator Microgravity Services (PIMS) project at the NASA GRC processes these data and can assist with tailored analysis or displays of the SAMS and MAMS data in support of principal investigators and other ISS customers upon request.

**Table 3 Acceleration Measurement Systems**

	SAMS		MAMS	
	RTS	TSH-ES	OSS	HiRAP
<b>Increment 36 Deployment</b>	3 triaxial sensors in USL 1 triaxial sensor in JEM 1 triaxial sensor in COL	1 triaxial in USL/FIR 1 triaxial in USL/CIR	1 triaxial sensor in USL	1 triaxial sensor in USL
<b>Description</b>	3 orthogonal accelerometers, QA-3100	3 orthogonal accelerometers, QA-3100	MESA sensor with calibration table	3 orthogonal accelerometers, pendulous
<b>Measured Quantity<sup>1</sup></b>	transient + vibratory, linear acceleration	transient + vibratory, linear acceleration	quasi-steady, linear acceleration	transient + vibratory, linear acceleration
<b>Bandwidth</b>	0.01 – 400 hertz	0.01 – 400 hertz	DC – 1 hertz	10 <sup>-4</sup> – 100 hertz
<b>Maximum Scale</b>	1.1 g @ gain = 1 0.11 g @ gain = 10	1.1 g @ gain = 1 0.13 g @ gain = 8.5	10 – 25 mg	16 mg
<b>Resolution</b>	0.1 ug	0.1 ug	3 – 4.6 ng	1 ug
<b>Dimensions (inches)</b>	5.9x4.5x3.4 (SE) 9.1x9.3x4.7 (EE)	4.45x3.65x3.53	21.9x18.4x23.6	
<b>Weight (lbs)</b>	2.5 (SE) 11 (EE)	1.3	117	
<b>Power (W)</b>	2.25 (SE) 8 (EE)	4.5 @ +/- 15 VDC 7.5 @ 28 VDC	79	
<b>Data Interface</b>	Ethernet	Ethernet, RS-232, USB	Ethernet	

## 6.1 How to Request SAMS Support

There are indirect methods to request SAMS support within the ISS program infrastructure. For example, you can submit an Operations Change Request (OCR) to the Enhanced HOSC System (EHS). However, the most direct method is to contact the Acceleration Measurement Program (AMP) manager at the NASA GRC. In this way, experienced knowledge of these acceleration measurement systems along with logistical considerations can be directly addressed. The best place to start that process is to send an email to [pimsops@grc.nasa.gov](mailto:pimsops@grc.nasa.gov). Some of the questions to consider for making a request for SAMS support are listed here:

- Spatial: where is your payload, and where can we mount a sensor to support you?
- Temporal: what GMT time frame(s) do you need SAMS support?
- Spectral: what frequency range governs your sensitivity or concern?

You may not know the answers to all of these questions up front, but the more you bring to the discussion, the better the service that can be provided right away. In addition, from these fundamental questions, a tailored set of displays or analysis can be discussed and possibly deployed to directly support your concerns.

By the way, why does this section only address SAMS? What about MAMS? That answer comes from the nature of each system's measurements. The SAMS is a distributed set of sensors intended to measure vibratory accelerations, which by their nature are localized. In this case, it is desirable to mount a sensor as close as practical to your payload in order to capture those local vibrations. On the other hand, the MAMS is a centralized system intended to measure the quasi-steady accelerations experienced onboard the ISS. By their nature, these quasi-steady accelerations tend to be global, not localized. At such low-frequencies in the quasi-steady regime, the space station can be assumed to be a rigid body. As such, the MAMS acceleration measurements made in the USL can be mathematically mapped to any arbitrary location on the ISS while accounting for gravity gradient and rotational effects that come with being displaced from the vehicle's center of mass.

<sup>1</sup> See Figure 1 Microgravity Environment Components.



## 7 Customers

The SAMS and MAMS were designed to support a broad array of scientific disciplines, including those affiliated with NASA's Physical Sciences Research Program. The AMP at NASA GRC offers analysis and measurement services for these scientific payload customers along with vehicle loads and dynamics analysis customers. In addition, NASA is committed to providing the U.S. segment of the ISS as a national laboratory. As a result, ongoing microgravity acceleration services are available for customers under that enterprise, and quite possibly you, as well.

### 7.1 Scientific Payloads

The ceilings, walls and floors of all three laboratories of the ISS are filled with racks, facilities and equipment. Much of this equipment is used in direct support of scientific investigations led by principal investigators, who went through extraordinary lengths in order to conduct their experiments in a microgravity environment. Their primary focus, of course, is on fundamental and applied research in fluid physics, combustion science, materials science, fundamental physics or complex fluids, but at least implicitly, they are also interested in the acceleration environment to which their payload is subjected. After all, these microgravity researchers are on the ISS to take advantage of the fact that their experiments, along with everything else in the space station, is free falling. For these scientists, phenomena that are gravity-driven (such as buoyancy, convection or sedimentation) may be undesirable, so they exploit free fall, which mitigates those effects to a great extent. The details, however, are in the microgravity environment record and ultimately manifest in their scientific results.

### 7.2 Vehicle Monitoring

The International Space Station represents an ambitious international collaboration. It is currently the largest, best-equipped space station ever constructed. It has been visited and inhabited by astronauts from 14 countries. Canada, Japan, Russia, Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, the United Kingdom and the United States all have a vested interest in its longevity and success. With an abundance of momentum, the ISS program at-large is interested in keeping the space station in orbit with a service life beyond its original plans. However, there are only so many cycles of flexing, bending, twisting and so on that key components of the space station can undergo before its structural integrity falls below acceptable levels of safety. With this in mind, there is a team of engineers at the NASA JSC that does daily assessments to provide feedback to the program in terms of this structural integrity and a crew at the NASA GRC that supports that effort. Much like a seismologist on Earth, these engineers use SAMS measurements to monitor the vibratory environment looking for significant microgravity acceleration events that would have an impact on the structural integrity of the ISS, then further analyze the acceleration measurements for those events to assess their impact on the vehicle. In addition to mode one monitoring, see Figure 5 Spectrogram Showing Crew Exercise Periods and Relative Quiet Period as another example that zooms out a bit. This gives structural analysts a qualitative look at, for example, the impact from crew exercise, with its signature visible between GMT 10:00 and 11:00 just below 3 hertz.

### 7.3 National Laboratory

The U.S. segment of the ISS has been designated as a National Laboratory. As such, the science facilities and acceleration measurement systems built by NASA are made available to private enterprise, such as commercial entities and universities, to pursue their own research objectives and applications under the auspices of the National Lab. The overall objective is to advance science, technology, engineering and mathematics from a platform with a unique environment available nowhere on Earth.

### 7.4 Perhaps You

If you are interested in ISS acceleration measurement or analysis services or know others who might benefit, but do not fit squarely into one of the headings listed in this section, then send an inquiry email to [pimsops@grc.nasa.gov](mailto:pimsops@grc.nasa.gov).

## 8 Primary Plot Types

The ISS program offers the SAMS and the MAMS to investigators, technology developers and vehicle analysts as a continuous means to monitor the acceleration environment. Furthermore, the PIMS team is available upon request to help analyze these acceleration measurements and therefore help evaluate the effects of the dynamic microgravity environment aboard the space station on your interests. Section 6 earlier showed three fundamental considerations when requesting acceleration measurement support. Those are in terms of spatial, temporal and spectral aspects of the environment. This section seeks to take the next step and convey several ways of examining acceleration data. Some of these are from an exploratory perspective and others take a keenly focused viewpoint. No single method, however,



should be regarded as the tell-all description to fully understand the acceleration environment and its effects. Each has strengths and weaknesses, but in combination or when correlated with other measurements or conditions these serve to help those interested to more fully understand the results of their experiments, technology or vehicle health.

## 8.1 Descriptions

For starters, it is important to recall that SAMS is intended to characterize the vibratory acceleration regime. Simply put, these are the relatively high-frequency, high-magnitude accelerations that should mostly be considered as localized to the sensor location. On the other hand, the MAMS is intended to characterize the quasi-steady acceleration regime. This is the relatively low-frequency, low-magnitude accelerations that are global in nature. Next, it is worthwhile to consider the descriptions in Table 4 Acceleration Analysis and Display Formats alongside the information provided in Figure 1 Microgravity Environment Components.

**Table 4 Acceleration Analysis and Display Formats**

Name	Regime(s)	Notes
Power Spectral Density (PSD) versus Frequency	vibratory	displays distribution of power with respect to frequency
Spectrogram (PSD versus Frequency versus Time)	vibratory	identify structure and boundaries in time and frequency displays power spectral density variations with time
Cumulative RMS Acceleration versus Frequency	vibratory	quantifies RMS contribution at and below a given frequency
Frequency Band(s) RMS Acceleration versus Time	vibratory	quantify RMS contribution over selected frequency band(s) versus time
RMS Acceleration versus One-Third Frequency Bands	vibratory	quantify RMS contribution over proportional frequency bands
Principal Component Spectral Analysis (PCSA)	vibratory	summarize magnitude and frequency excursions for key spectral contributors over a long period of time results typically have finer frequency resolution and high PSD magnitude resolution relative to a spectrogram at the expense of poor temporal resolution
Acceleration versus Time	vibratory transient quasi-steady	precise accounting of measured data with respect to time best temporal resolution
Interval Min/Max Acceleration versus Time	vibratory quasi-steady	displays upper and lower bounds of peak-to-peak excursions of measured data good display approximation for time histories on output devices with resolution insufficient to display all data in time frame of interest
Interval Average Acceleration versus Time	vibratory quasi-steady	provides a measure of net acceleration of duration greater than or equal to interval parameter
Interval RMS Acceleration versus Time	vibratory	provides a measure of effective amplitude versus time
Trimmed Mean Filtered Acceleration versus Time	quasi-steady	removes infrequent, large amplitude outlier data to give residual acceleration versus time
Quasi-Steady Mapped Acceleration versus Time	quasi-steady	use rigid body assumption and vehicle rates and angles to compute acceleration at any location attached to the vehicle
Quasi-Steady Three-Dimensional Histogram (QTH)	quasi-steady	summarize acceleration magnitude and direction for a long period of time indication of acceleration "center-of-time" via projections onto three orthogonal planes

## 8.2 Where do I Start Exploring the Space Station's Acceleration Environment?

Roadmaps are a good place to start when exploring. For the vibratory acceleration regime, start navigating by date at the following link <http://pims.grc.nasa.gov/roadmap/>. Click a date on the left, then on a link for a plot on the right. These roadmap spectrogram products are updated daily, extend back to the early days of the ISS and provide a good overview starting point. For the quasi-steady regime, start at the following link <http://pims.grc.nasa.gov/plots/batch/Quasi-steady/>.

For recent data, that have not been turned into roadmaps yet, start at the following link <http://pims.grc.nasa.gov/plots/user/buffer/> where you will find a sequence of screenshots from the real-time displays maintained at the NASA GRC Telescience Support Center in Cleveland, Ohio.

Finally, for near real-time data, visit this link [http://pims.grc.nasa.gov/pims\\_iss\\_index.html](http://pims.grc.nasa.gov/pims_iss_index.html) and use the menu under the "Current Real-Time" seen toward the upper left and see what's shaking, so to speak, on the space station. If none of these products fit your need, then consider a custom request to [pimsops@grc.nasa.gov](mailto:pimsops@grc.nasa.gov).

## 9 Vibration Isolation

The ISS offers a microgravity research platform that is unrivaled in the known universe, past and present. At the same time, there are many creative minds attempting to examine and study biological and physical phenomena that push the cutting edge of technology. Measurement or detection apparatus designed to peer with unprecedented precision inward at fundamental physics, fluids, combustion and material science or looking outward at distant cosmology, for example, attempting to determine the radii of neutron stars to within  $\pm 5$  percent. For these researchers, even the microgravity environment provided by the ISS platform itself still perturbs their experiment or the equipment needed to make their measurements or observations. They need some form of isolation in order to attenuate the vibrations to which their experiment is subjected.

In general, there are two basic types of vibration isolation currently in use on the ISS. There is a passive type that requires no electrical power or control mechanism to achieve the vibration isolation. Also, there is an active type that requires both electrical power and a sophisticated control system to work. The table<sup>2</sup> below shows a comparison of these two approaches.

**Table 5 Vibration Isolation Approaches**

Vibration Isolation System	Type	Advantages	Disadvantages
Passive Rack Isolation System (PaRIS)	passive	low cost low maintenance reliable no power	isolate only higher frequencies requires large volume cannot mitigate payload induced vibrations resonance versus attenuation tradeoff
Active Rack Isolation System (ARIS)	active	low-frequency performance multiple payloads standardized user interface	high maintenance sensitive to crew contact cannot mitigate payload induced vibrations requires "good neighbors"

### 9.1 Passive Vibration Isolation of the Combustion Integrated Rack (CIR)

The Fluids and Combustion Facility (FCF) takes on the technical challenges of experimenting with fluids and combustion in microgravity and provides the services and capabilities for conducting cutting-edge research in these disciplines. The Combustion Integrated Rack (CIR) is part of the FCF and the only combustion research facility onboard the ISS. The CIR includes a combustion chamber, fuel and oxidizer control and a number of cameras for performing combustion experiments. The CIR is situated such that it can be used with the Passive Rack Isolation System (PaRIS), which provides a non-rigid mechanical connection between the CIR and ISS structure using eight spring-damper isolators and umbilical cables.

<sup>2</sup> The information in this table was based on a presentation given by Dr. Mark Whorton at a Microgravity Environment Interpretation Tutorial (MEIT) in 2004.

Analysis of SAMS measurements show that the PaRIS provides attenuation as a function of frequency, more so at higher frequencies. The blue trace PSDs plotted in Figure 11 Power Spectra Showing Passive Attenuation from PaRIS shows the magnitude roll-off with frequency associated with the SAMS sensor mounted on the CIR relative to the red trace PSDs on that same plot associated with a different SAMS sensor mounted on a non-isolated rack. The following table gives a different view of this attenuation broken down into five frequency bands:

**Table 6 Comparison Showing PaRIS Attenuation for the CIR**

Frequency Range (hertz)	ugRMS	
	Non-Isolated Rack	PaRIS- Isolated CIR
	SAMS 121f03	SAMS es05
0.01 - 1	13	13
1 - 2	85	41
2 - 3	69	26
3 - 4	34	10
4 - 5	15	4

The reader is encouraged to refer to the last page of the handbook entry titled “Exercise PaRIS” at the following link [http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb\\_vib\\_crew\\_exercisecomparison.pdf](http://pims.grc.nasa.gov/pimsdocs/public/ISS%20Handbook/hb_vib_crew_exercisecomparison.pdf) to see the dramatic difference in acceleration magnitudes in a plot of acceleration vector magnitude versus time. There you will see that the SAMS data (low-pass filtered at 6 hertz), shows acceleration magnitudes at the non-isolated rack location averaged about 105 ug during this crew exercise period, while the average was about 47 ug at the PaRIS-isolated CIR location. This example shows a quieter acceleration environment with PaRIS than otherwise would be achieved with a hard-mounted rack.

## 9.2 Active Vibration Isolation of the Fluids Integrated Rack (FIR)

The Fluids Integrated Rack (FIR) in the FCF provides facilities for conducting microgravity fluid physics research on boiling, cooling, colloids, gels, bubbles, wetting and capillary action. The FIR is located in an ARIS rack. The ARIS acts to help isolate payloads that reside within the rack from disturbances that originate external to the rack. It employs sensors that detect external disturbances propagating through space station structure and actuators that work to counter the effects of these vibrations. It does so by generating a reactive force between the payload rack and the structure to which it is attached. ARIS is a finely tuned system with multiple components, a sophisticated control algorithm and a fair bit of overhead and logistics to consider.

Analysis of SAMS measurements show that the ARIS also provides attenuation, but in this case the attenuation is more so at frequencies below 20 hertz. The blue trace PSDs plotted in Figure 12 Power Spectra Showing Active Attenuation from ARIS shows the magnitude roll-off with frequency below 20 hertz associated with the time span when ARIS was on relative to the red trace PSDs in that same figure associated with a different time span for the same SAMS sensor location on the FIR when ARIS was off. The following table gives a different view of this attenuation broken down into two frequency bands:

**Table 7 Comparison Showing ARIS Attenuation for the FIR**

Frequency Range (hertz)	GMT	ugRMS	
		ARIS off	ARIS on
0.01 - 20	02-Aug-2011	105	9
	05-Aug-2011	96	12
20 - 200	02-Aug-2011	486	479
	05-Aug-2011	480	469

Note the large differences in acceleration RMS magnitudes below 20 hertz on two different days when comparing when ARIS was on versus when it was off. By contrast, you can see that above 20 hertz, there is not significant attenuation afforded by the ARIS.

### 9.3 Time/Location “Vibration Isolation”

When used as designed, both the passive and active vibration isolation systems onboard the ISS will deliver a quieter microgravity environment as shown in the examples above. However, those vibration isolation systems come with overhead, logistics and constraints such that not all payloads can be accommodated. For interested payloads that cannot be obliged in this way, knowledge is power. Knowledge of the microgravity environment can be leveraged to find quiet times and/or quiet places.

For an example of quiet time, consider the effects of crew activity. The vibratory impact from the crew (exercise, experiment ops, locomotion) goes away for hours at a time during crew sleep. If you can conduct sensitive parts of your procedure without need for the crew, then these are predictable times you can exploit.

Figure 13 RMS versus Time for Five Days with Blue Dots during Sleep Periods (0.01 – 0.1 hertz) is a plot of RMS acceleration versus time for five consecutive days. The RMS value comes from a portion of the acceleration spectrum between 0.01 and 0.1 hertz and clearly shows that during sleep (shown with blue dots and ending each day with wake at GMT 06:00), the low end of the structural mode regime gets much quieter. Crew motion tends to excite low-frequency vibrations in large space station structures, so crew sleep allows for much of those vibrations to die down.

Figure 14 RMS versus Time for Five Days with Blue Dots during Sleep Periods (0.0101 – 6 hertz) is a plot of RMS acceleration versus time for the same five consecutive days as the previous figure. The RMS value comes from a portion of the acceleration spectrum between 0.01 and 6 hertz and also shows similar quieting during sleep.

Figure 15 RMS versus Time for Five Days with Blue Dots during Sleep Periods (0.101 – 30 hertz) is a plot of RMS acceleration versus time for again the same five consecutive days. The RMS value comes from a portion of the acceleration spectrum between 0.01 and 30 hertz and does not show significant quieting during sleep. This portion of the acceleration spectrum is dominated by higher frequency disturbance sources above about 6 hertz (e.g., Ku-band antenna) that does not benefit from crew sleep.

The table below shows results from acceleration analysis performed in support of the Cold Atom Laboratory sponsored by the NASA Jet Propulsion Laboratory (JPL). The GMT span covered is the same five days as those shown in the previous three figures. These results reinforce the assertion that below about 6 hertz there is a statistically quieter microgravity environment owing to less excitation of structural modes during crew sleep. Conversely, when we consider up to 50 hertz, there is no benefit to crew sleep periods in this regard. Again, other higher-frequency disturbance sources dominate here.

**Table 8 Five-Day Statistical Summary Comparison of Crew Sleep to Wake (SAMS 121f04 LAB102)**

Frequency Range (hertz)	Crew	ugRMS			
		Mean	Standard Deviation	Minimum	Maximum
0.01 - 0.1	sleep	0.2700	0.1487	0.1231	1.6116
0.01 - 0.1	wake	1.6701	1.1483	0.1404	16.1994
0.01 - 6	sleep	13.2523	6.9151	6.5849	93.5371
0.01 - 6	wake	26.2189	11.7456	7.9301	106.8510
0.1 - 50	sleep	1155.3400	43.0793	1029.2800	1276.7200
0.1 - 50	wake	1117.6400	81.6025	936.7740	4402.2300

This comparison of crew sleep to wake shows one way of leveraging your schedule to gain some respite from the vibratory impact below about 6 hertz. In an orthogonal sense, the location of your payload can also offset or help mitigate the impact of vibrations on your payload.

Consider a few locations that were simultaneously measured by SAMS sensors in each of the three laboratories for eight hours starting at GMT 17-Dec-2012, 352/08:00. Comparing the spectrogram of Figure 16 Monitor Mode One with SAMS Sensor in USL to the corresponding ones from Figure 17 Monitor Mode One with SAMS Sensor in JEM and Figure 18 Monitor Mode One with SAMS Sensor in COL to see qualitatively that the SAMS sensor in the USL for the structural mode regime is not as harsh as those in the JEM or the COL. The table below summarizes this with a focus strictly on the lowest mode at around 0.1 hertz.

**Table 9 Comparison of Mode One SAMS Measurements in All Three Laboratories**

Laboratory	SAMS Sensor	ugRMS
USL	121f03	1.839
JEM	121f05	3.133
COL	121f08	3.138

The comparison here of the structural mode regime between the three laboratories says nothing about the higher-frequency environment at those locations. Different portions of the spectrum at different locations throughout the space station are subject to their vibratory neighborhood. Nevertheless, it can be seen that location can provide another approach to governing the acceleration environment you inhabit.

## **10 References**

For good background information on microgravity environment, see [http://pims.grc.nasa.gov/MMAP/PIMS\\_ORIG/MEIT/meit2004pdfs.html](http://pims.grc.nasa.gov/MMAP/PIMS_ORIG/MEIT/meit2004pdfs.html).

For more details on acceleration analysis methods, see [http://pims.grc.nasa.gov/MMAP/PIMS\\_ORIG/PDFs/ADAPT.pdf](http://pims.grc.nasa.gov/MMAP/PIMS_ORIG/PDFs/ADAPT.pdf).

**11 Appendix 1 for Figures (labeled with prefix “FigKH”)**

# Microgravity Environment Components

a generic label,  
not intended to  
quantitatively  
characterize the  
platform

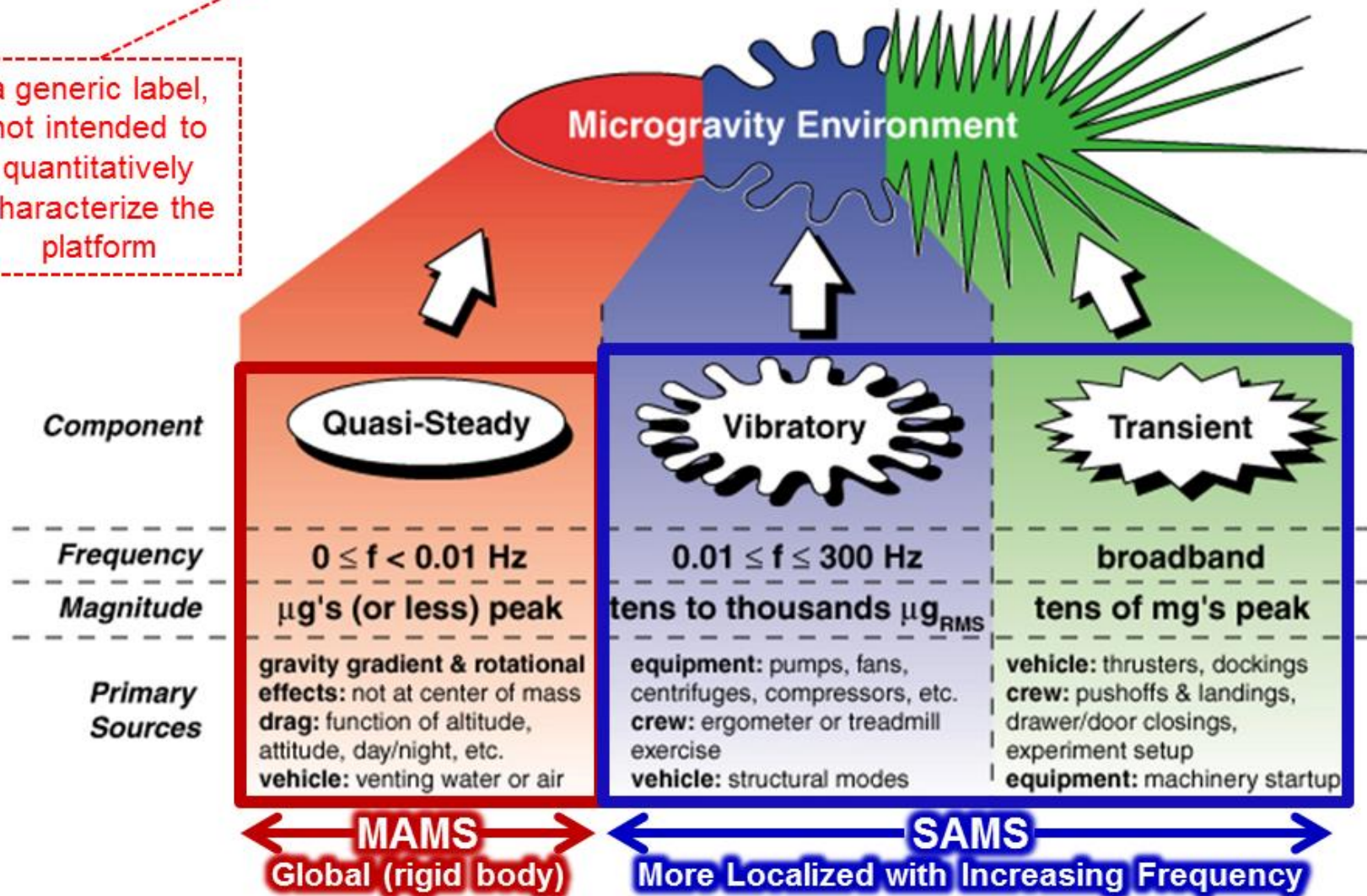


Figure 1 Microgravity Environment Components



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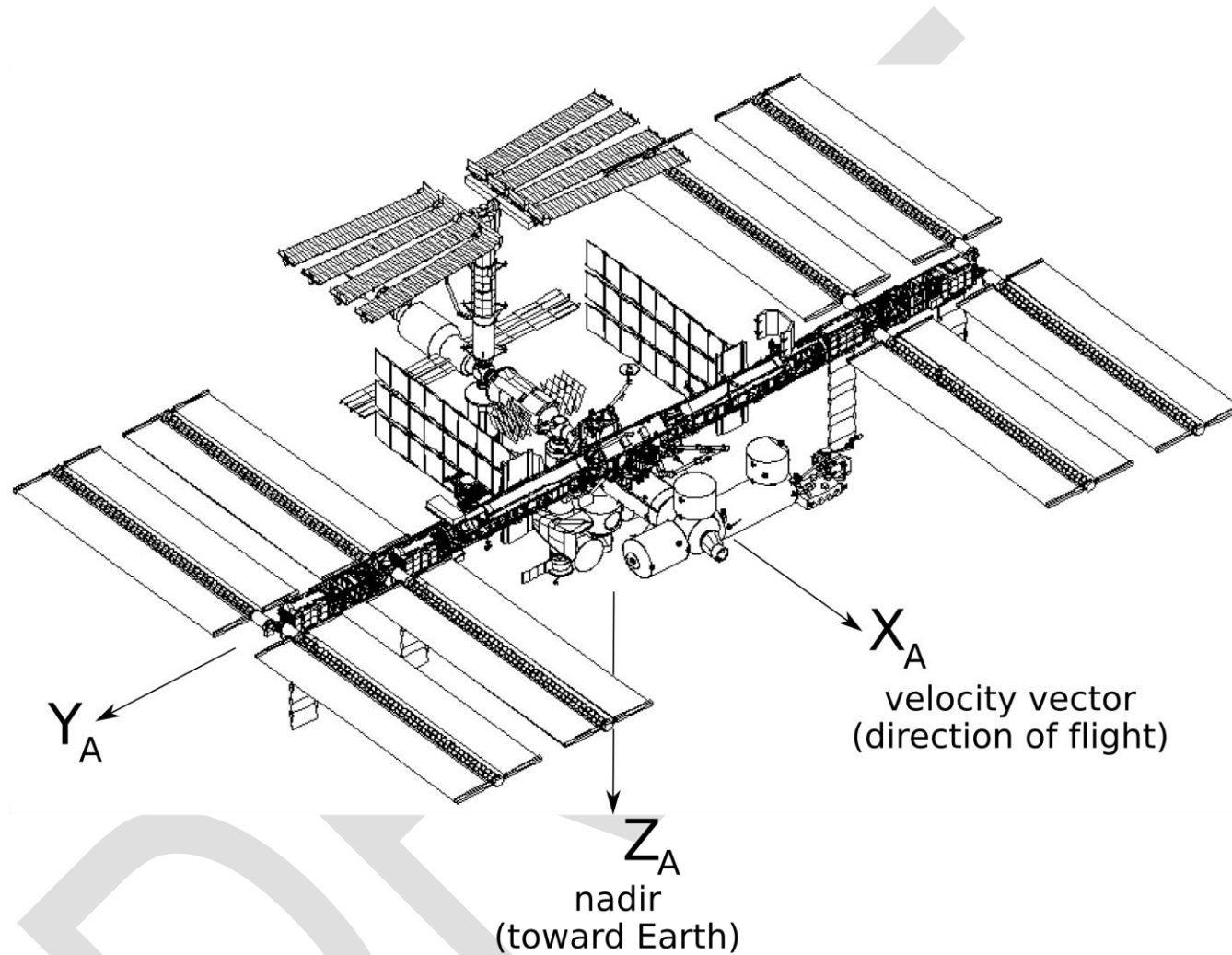


Figure 2 Space Station Analysis (SSA) Coordinate System

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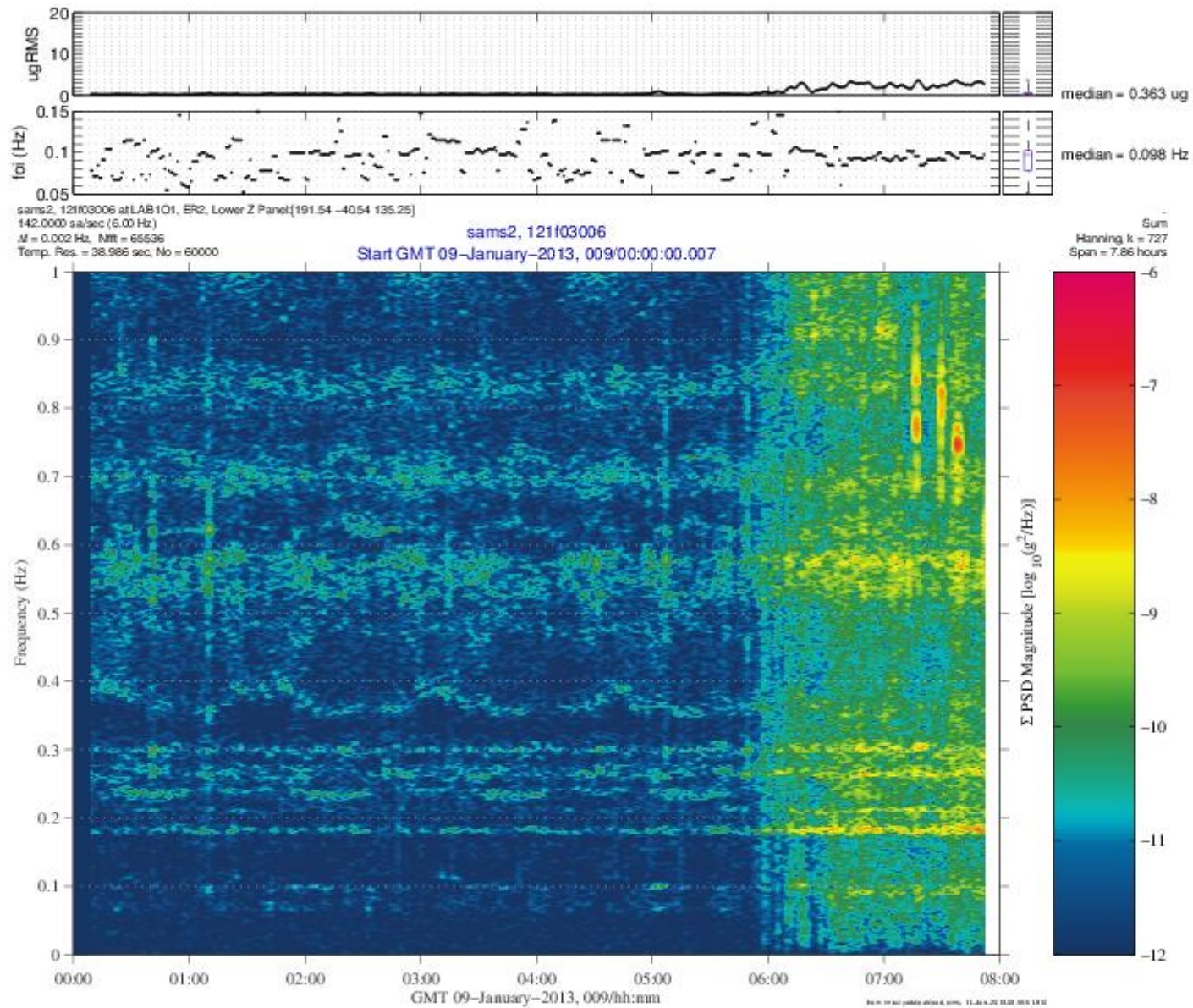


Figure 3 Spectrogram Showing Mode One with Crew Sudden Transition to Wake

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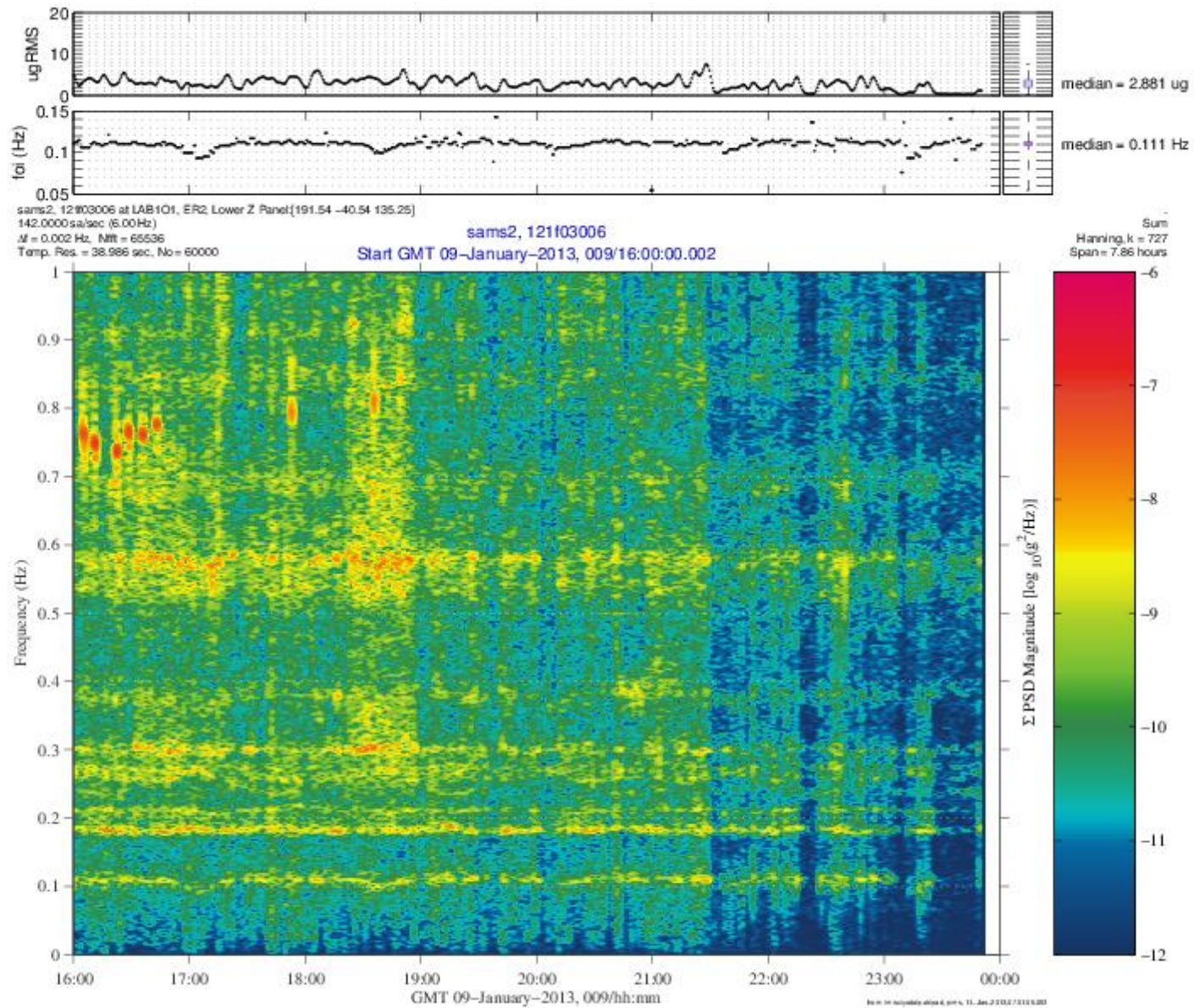


Figure 4 Spectrogram Showing Mode One with Crew Slow Transition to Sleep



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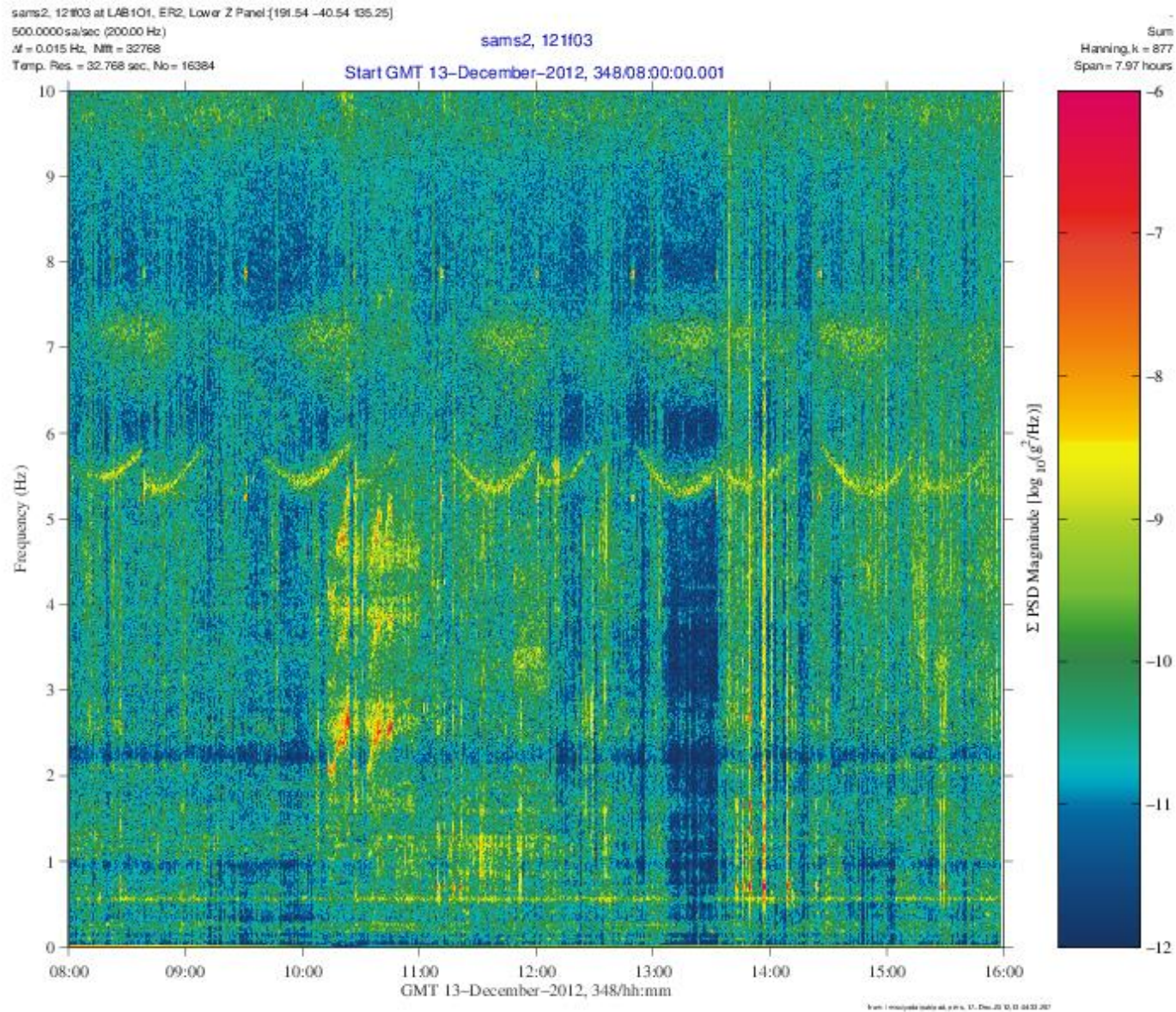


Figure 5 Spectrogram Showing Crew Exercise Periods and Relative Quiet Period



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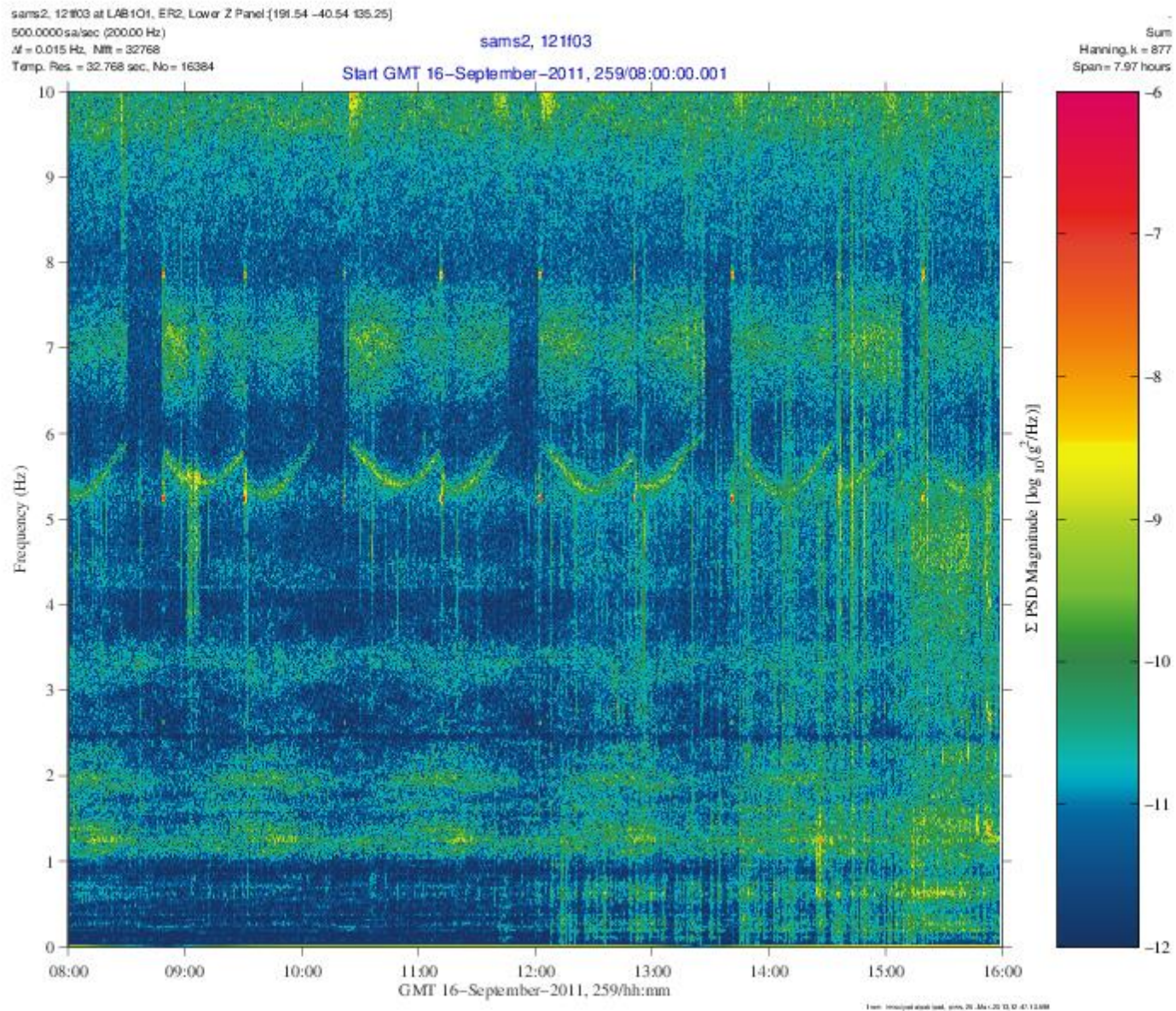


Figure 6 Spectrogram Showing Ku-Band Acquisition Signature

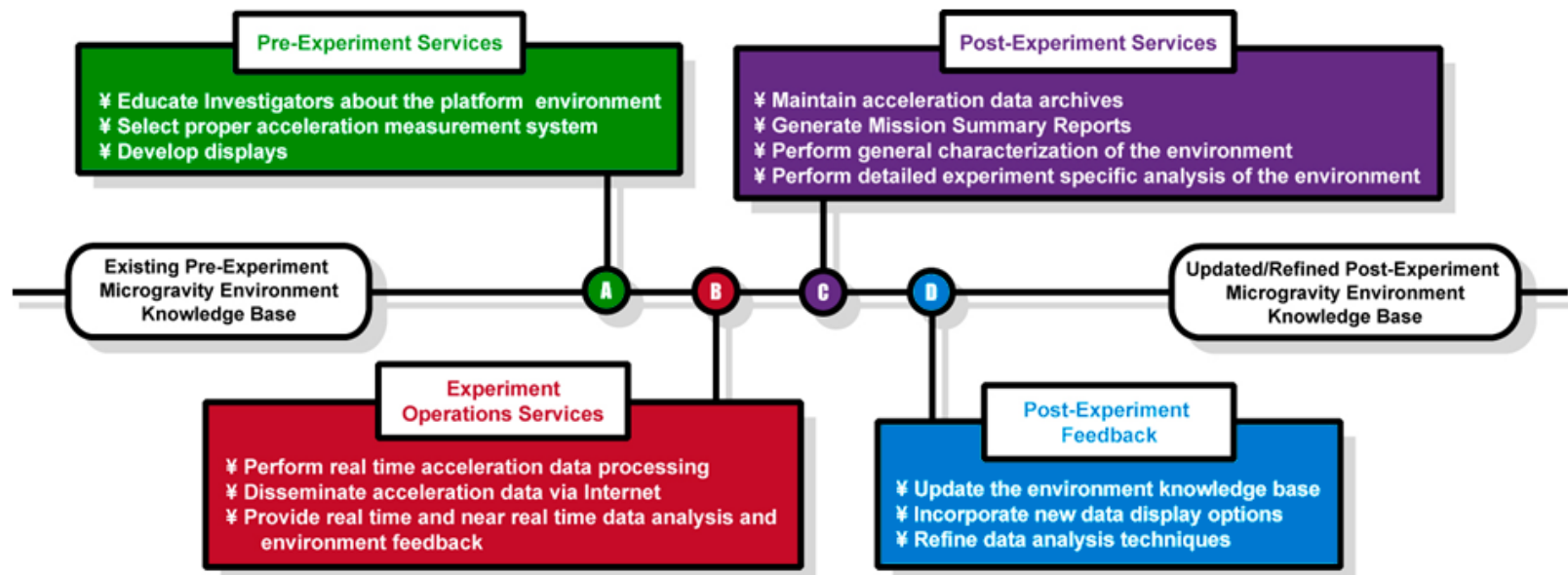
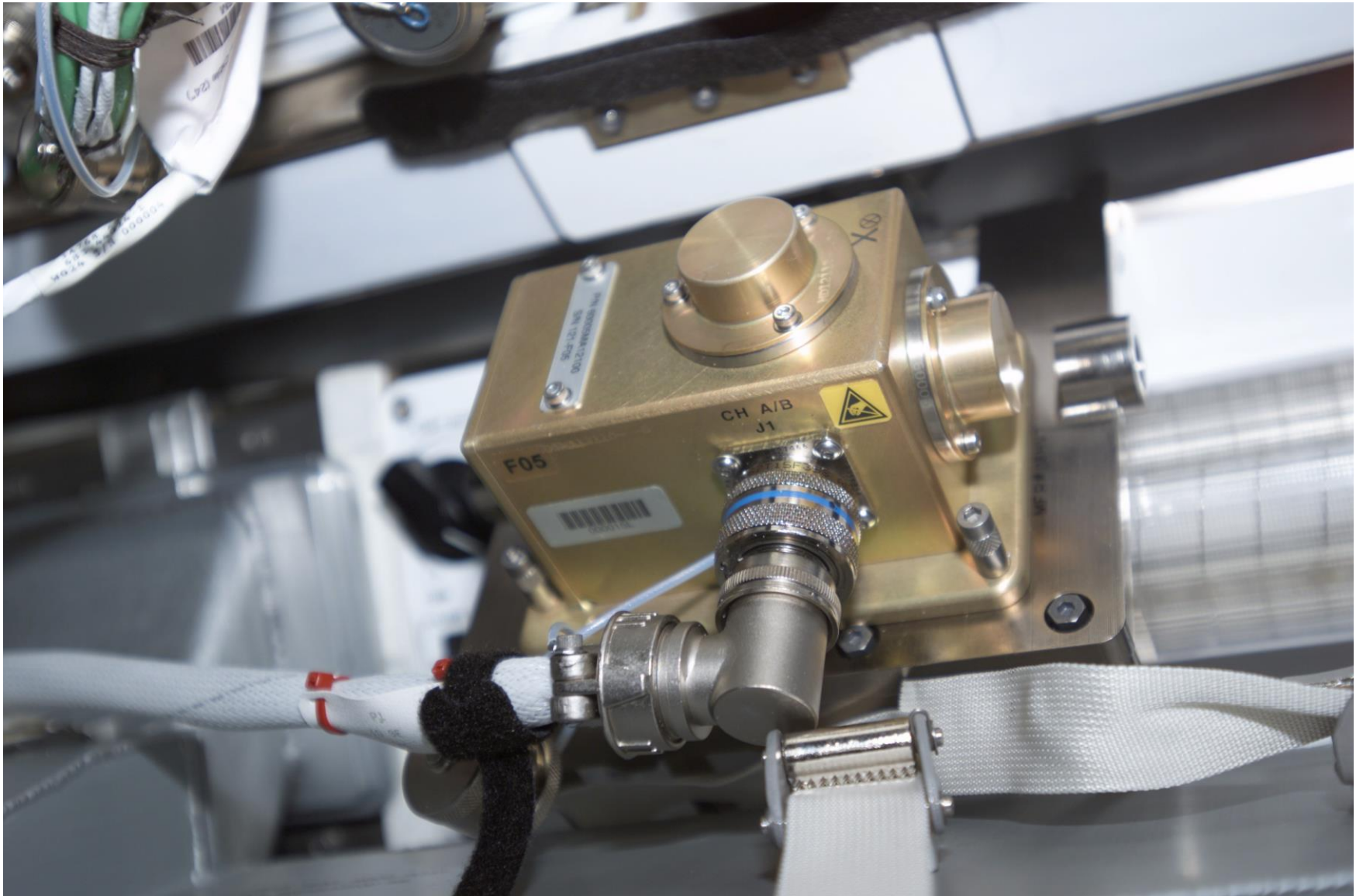


Figure 7 Acceleration Environment Feedback Model





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Figure 8 On-Orbit Photo of SAMS Sensor in USL during Expedition 4

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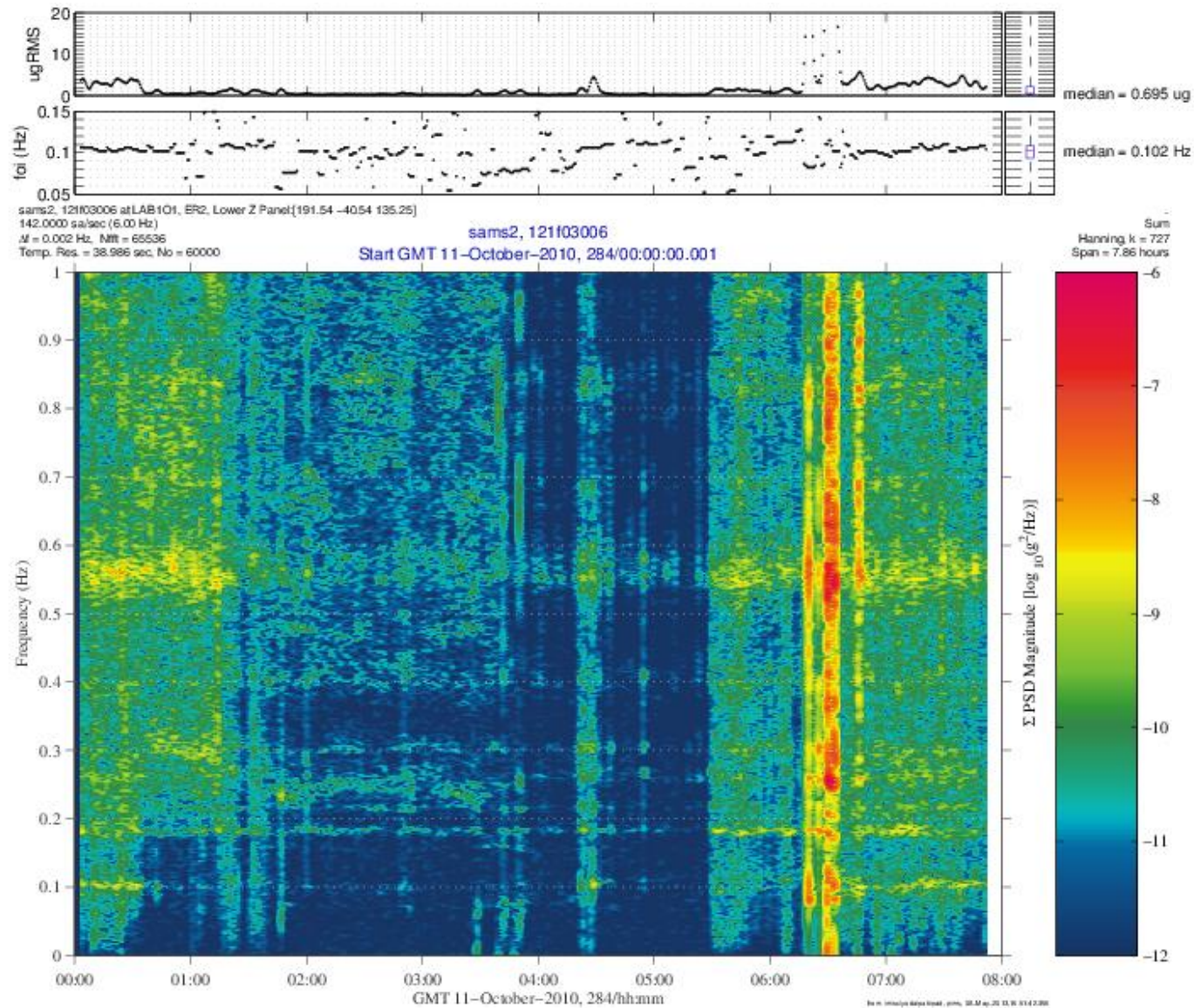


Figure 9 Sample of Daily Products Used to Monitor Loads Events for Structural Integrity



## ISS Acceleration Archive at NASA GRC

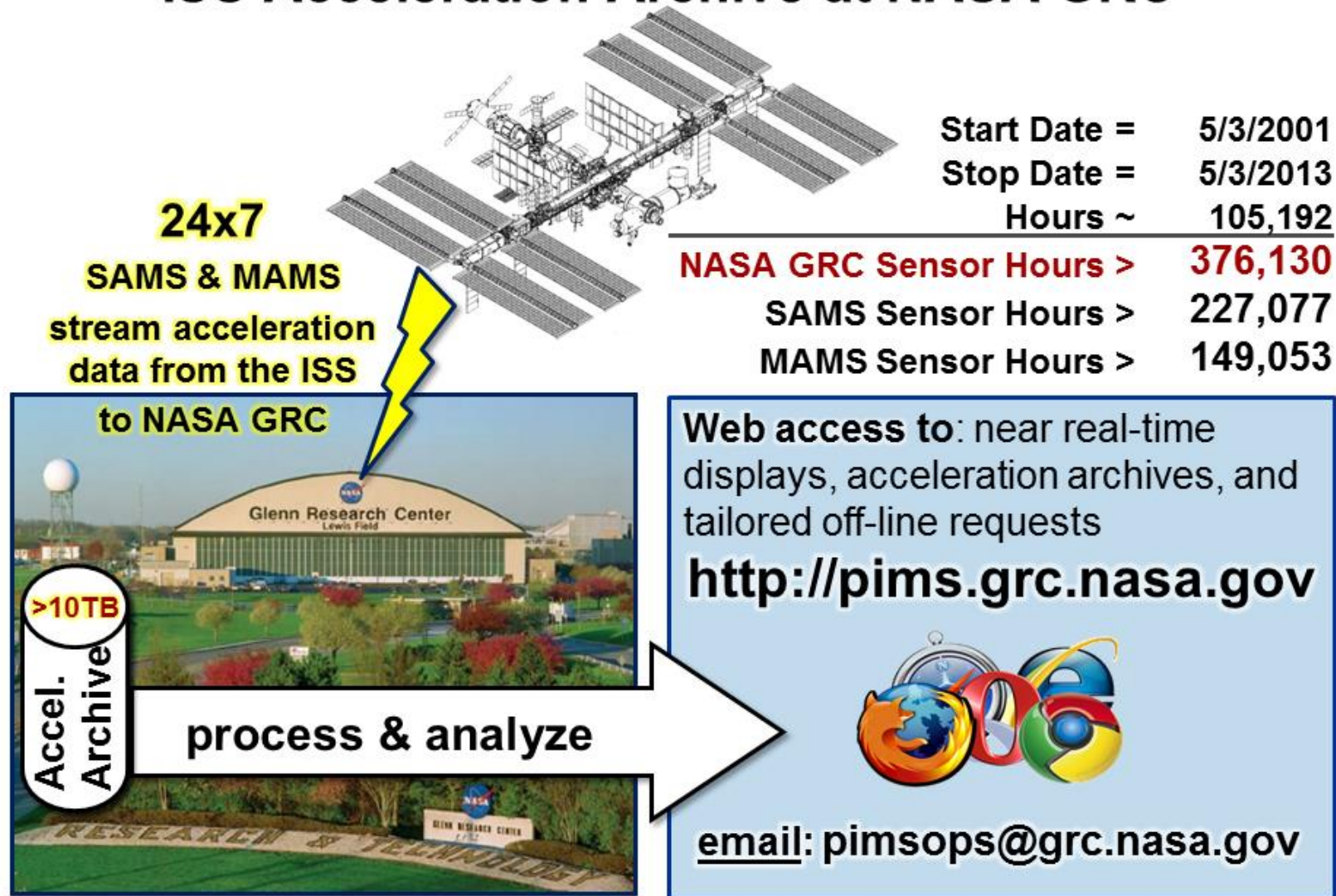
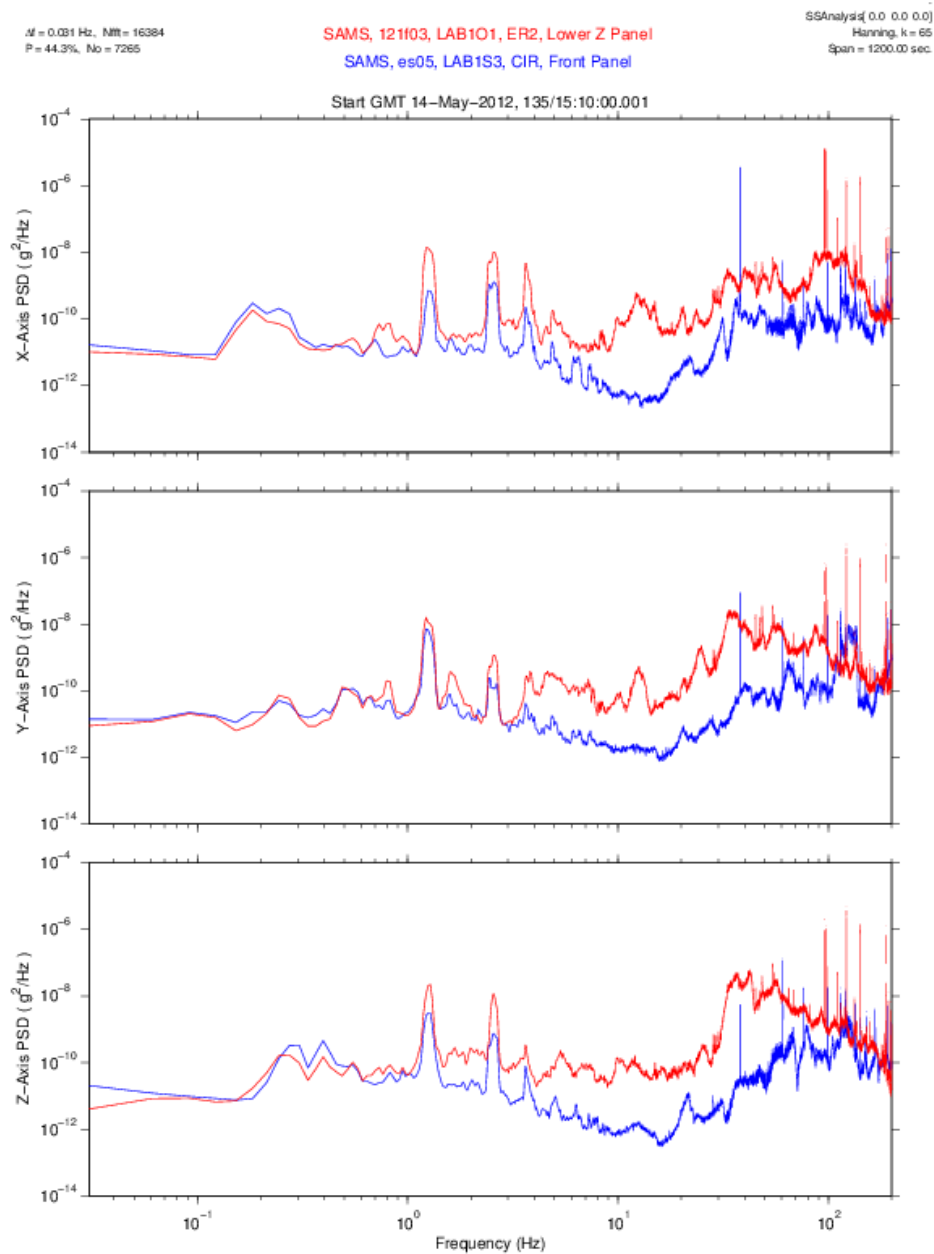


Figure 10 Acceleration Data Archives

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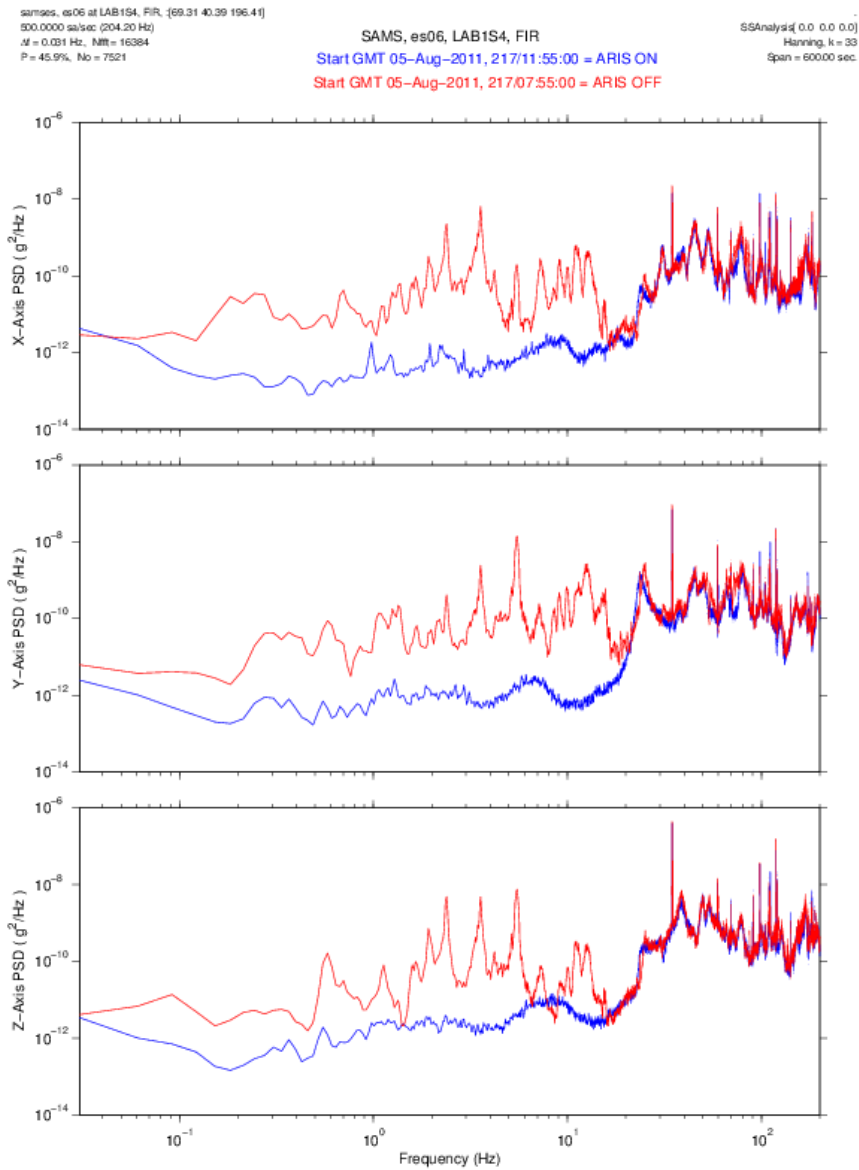
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**Figure 11 Power Spectra Showing Passive Attenuation from PaRIS**

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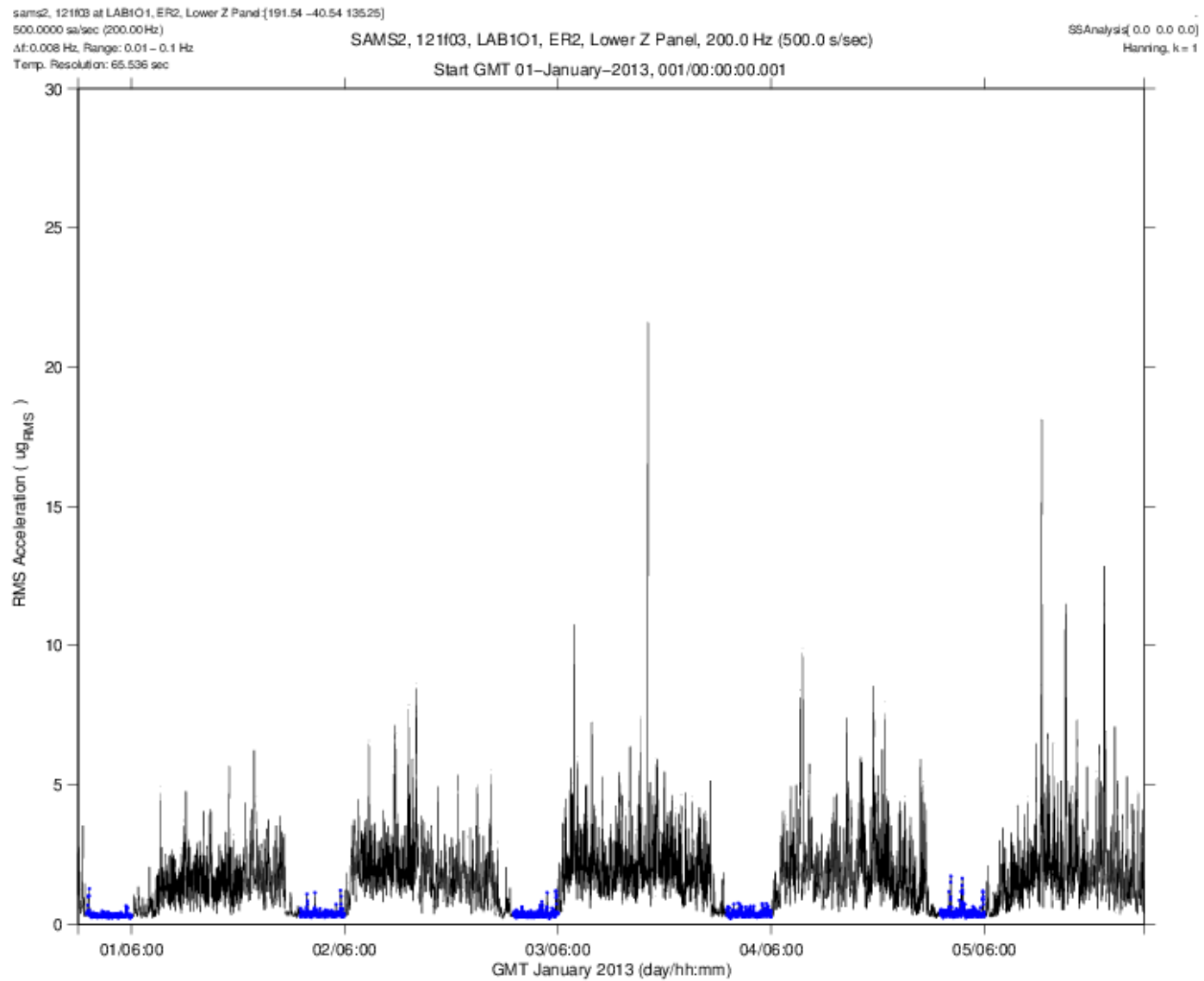
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**Figure 12 Power Spectra Showing Active Attenuation from ARIS**

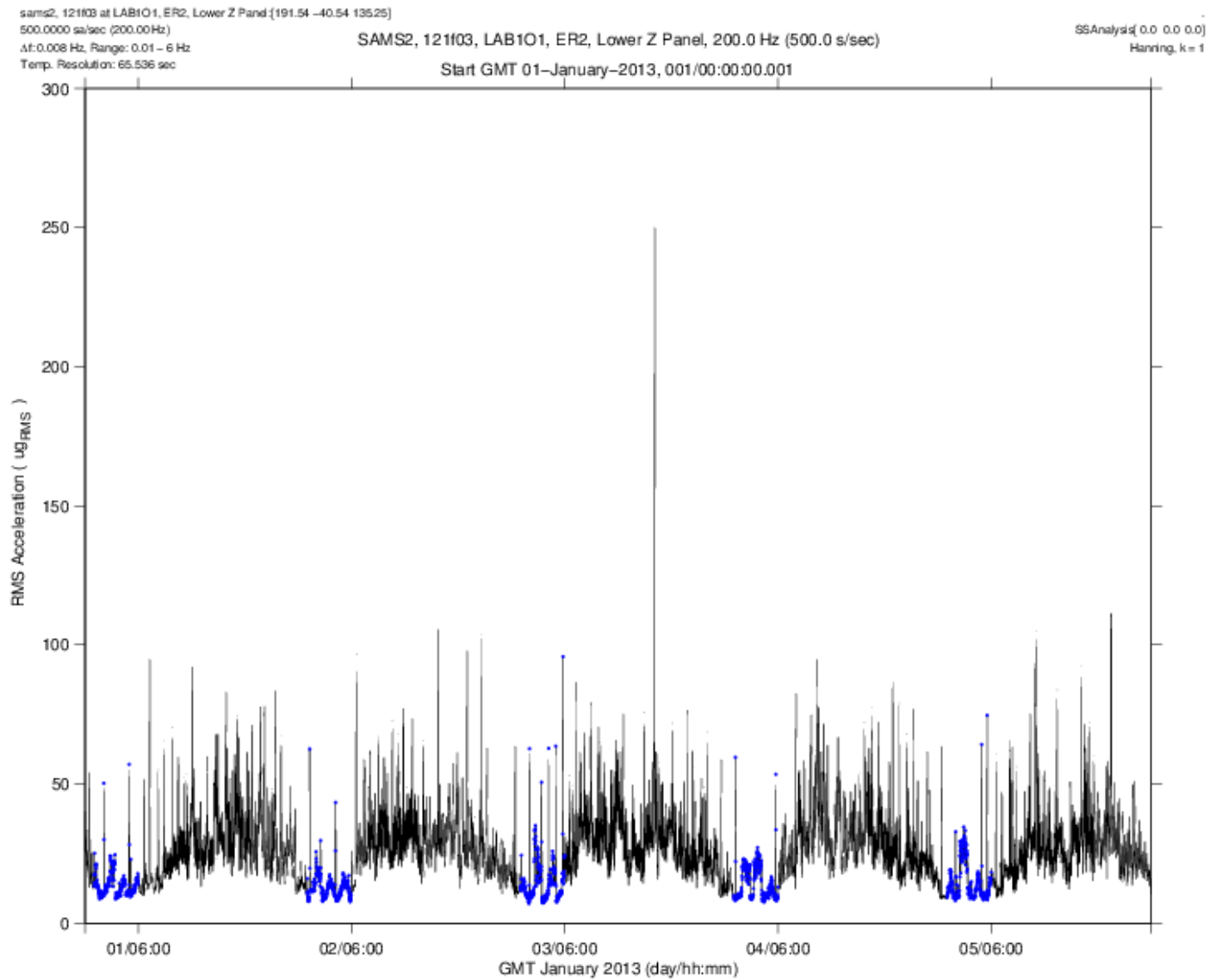


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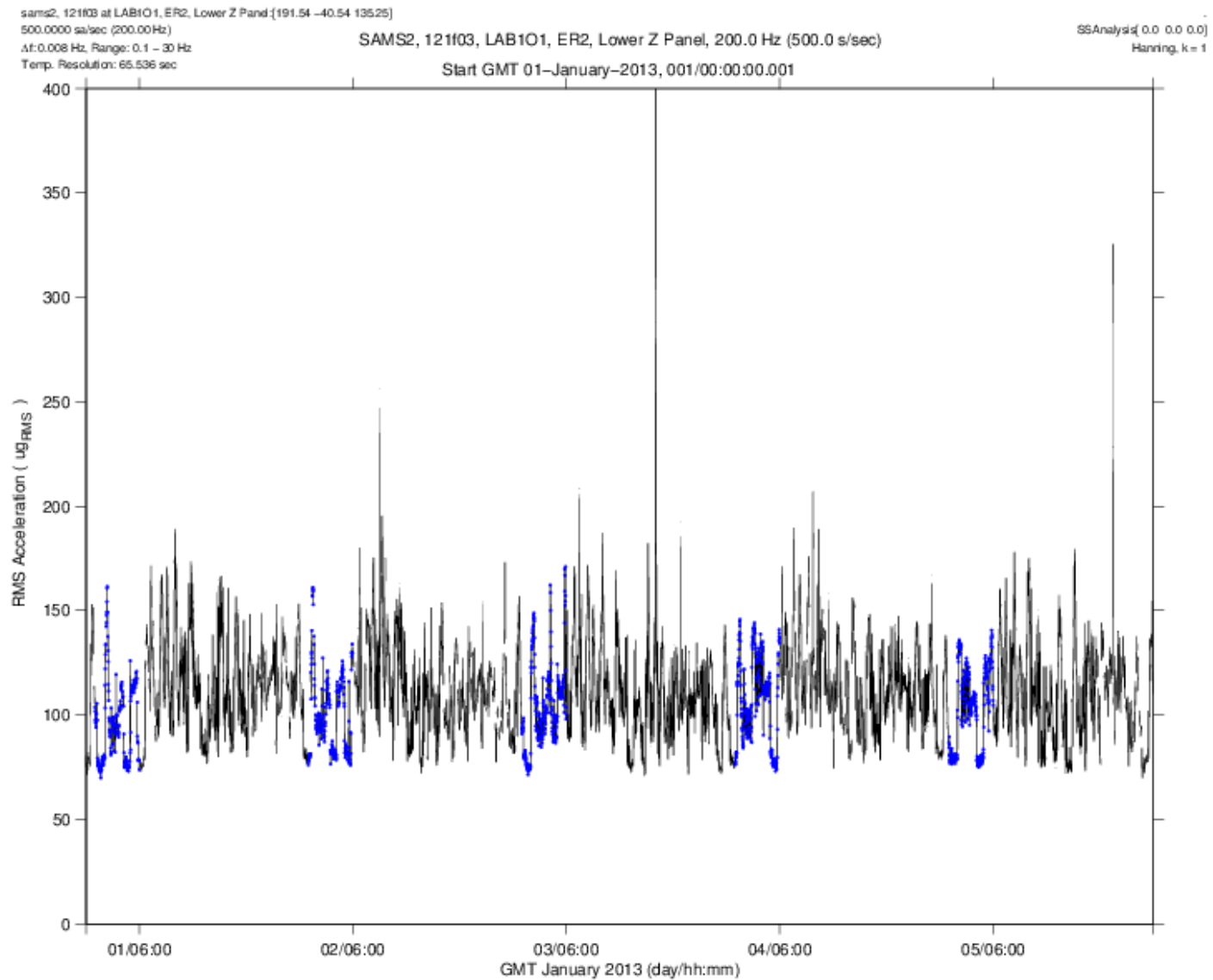
**Figure 13 RMS versus Time for Five Days with Blue Dots during Sleep Periods (0.01 – 0.1 hertz)**

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**Figure 14 RMS versus Time for Five Days with Blue Dots during Sleep Periods (0.0101 – 6 hertz)**

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**Figure 15 RMS versus Time for Five Days with Blue Dots during Sleep Periods (0.101 – 30 hertz)**

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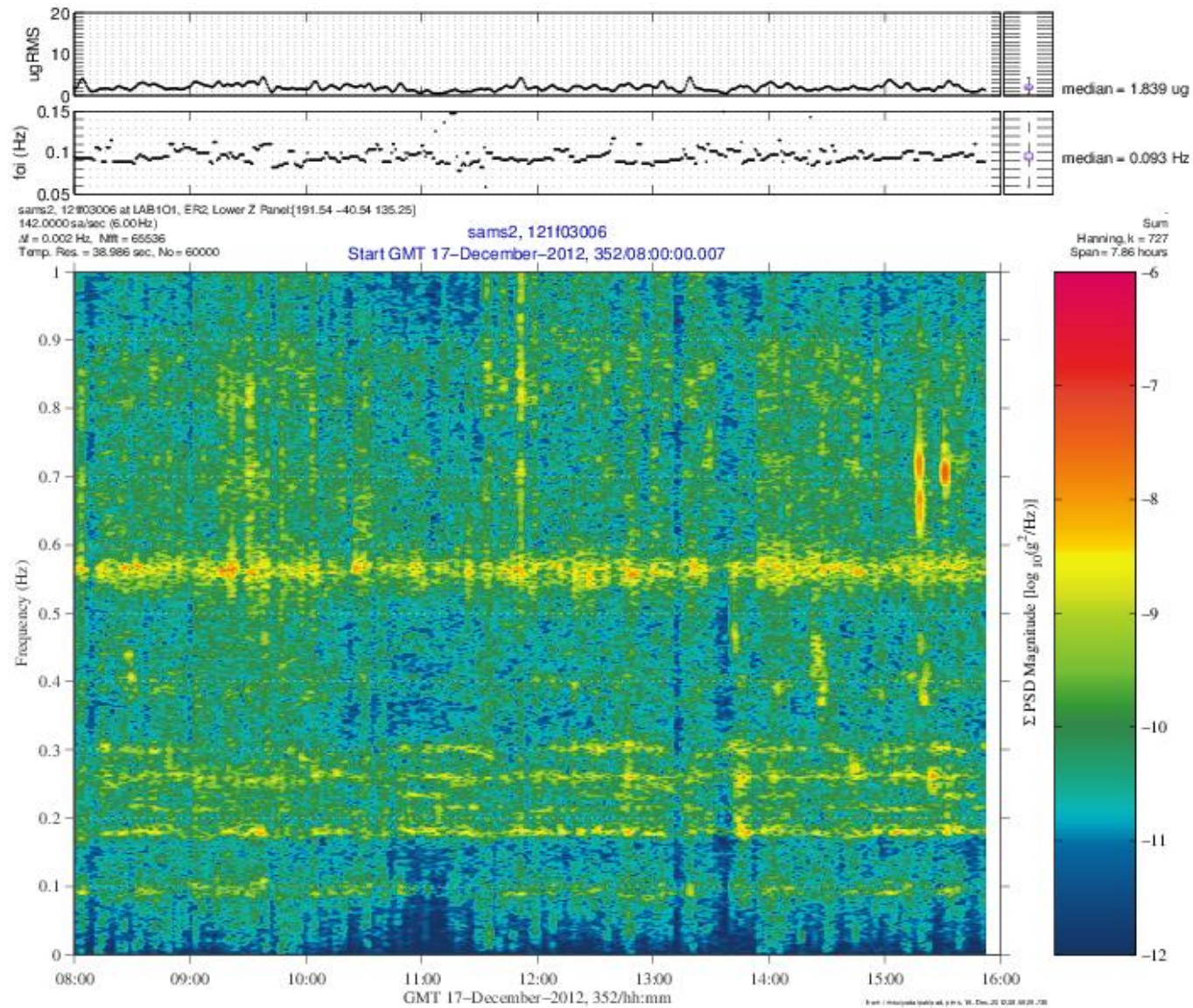


Figure 16 Monitor Mode One with SAMS Sensor in USL



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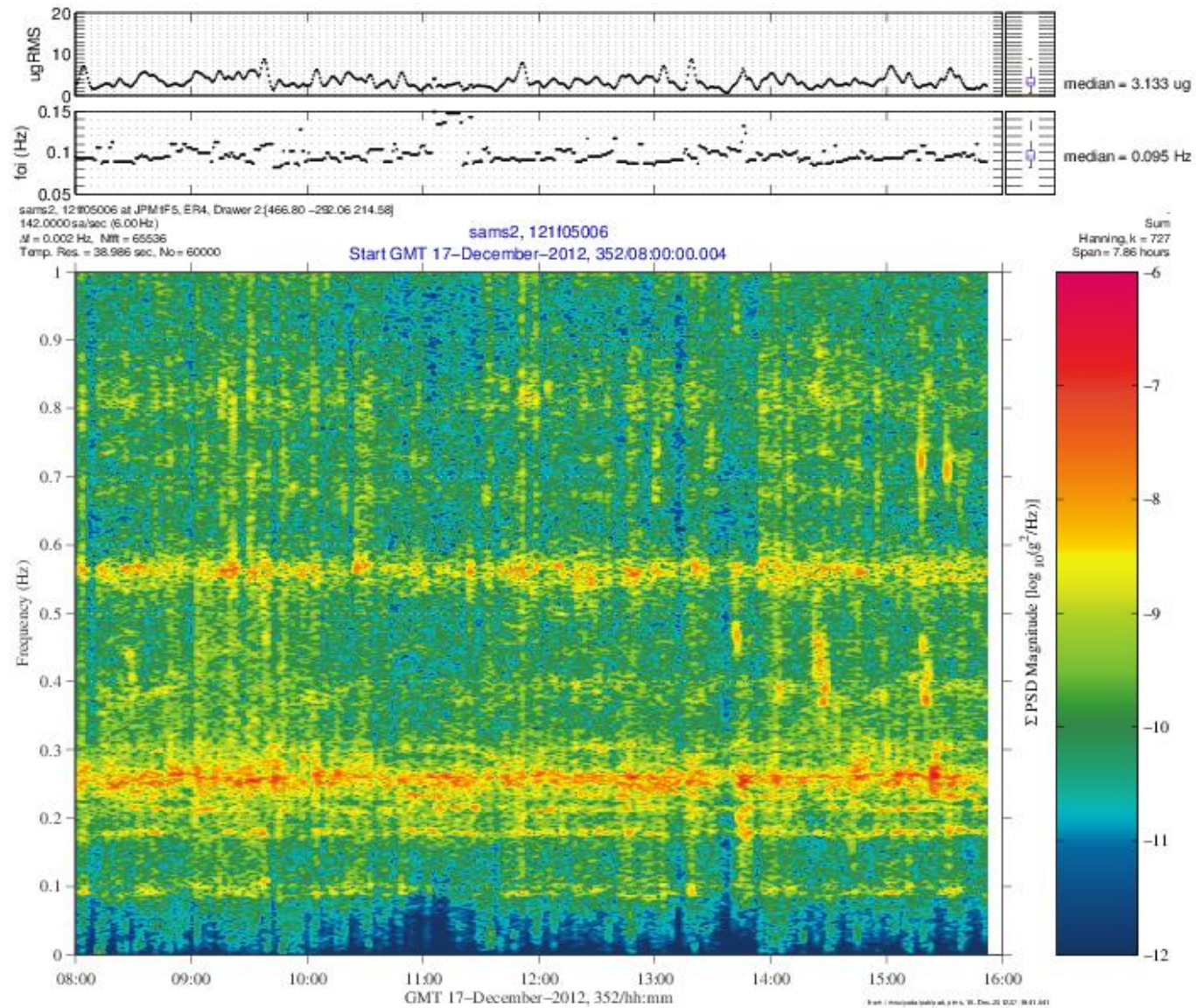


Figure 17 Monitor Mode One with SAMS Sensor in JEM

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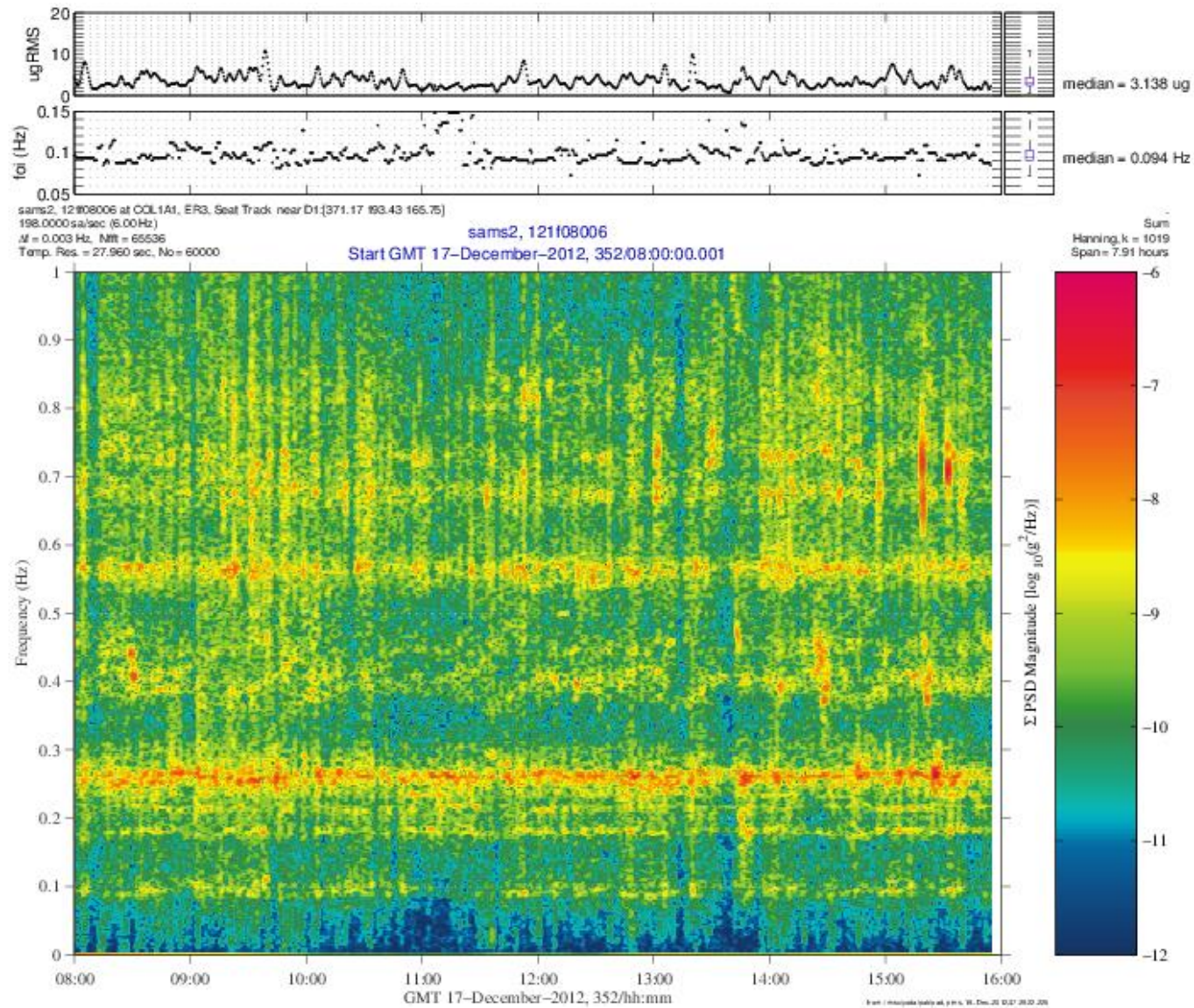


Figure 18 Monitor Mode One with SAMS Sensor in COL